TIRE DAMPER

by

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ABSTRACT

This research was undertaken to investigate an unusual and innovative sustainable approach to improve the structural performance of buildings. It was the hope at the start of this project that it would demonstrate results that are similar to modern day dampers at a fraction of the cost. This damper design is termed a Tire Damper and requires a braced frame, inexpensive pin connections, concrete, reinforcing bars or rods, a used tire, duct tape, and four steel plates. The reuse of materials involved and its low cost give this damper the potential to be used.

The Tire Damper developed may be able to be improved with additional research, but has shown great potential during analysis of the data. It has proven to be an effective design element which can be used in many different scenarios, from low rise buildings to industrial buildings.

This thesis is dedicated to my dad James Michael Pearce for showing me that a positive attitude and an extraordinary work ethic can bring you the highest level of happiness and achievement in life, to my mom Joyce Lynn Meldrum Pearce for helping me to succeed in life while putting care for others before myself, and to my grandparents Floyd and Jeri Meldrum for their unending and unconditional love and support.

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1 INTRODUCTION

1.1 General

This research was carried out in an effort to investigate a tire damper which could provide seismic structural strength at a very low cost to low-rise buildings. The seismic capacity of a typical structure could be significantly increased with the simple tire damper design which is presented in this thesis. The damper increases the linear deformation of the structure, and may reduce nonlinear deformation. This will result in less overall deformation within the structure. Additionally, the design that was created is sustainable, easy to assemble, and requires few new materials. Some of the materials from the damper can be reused after a major event.

A damper is a system which absorbs and dissipates energy that might come from ground vibrations. The reason dampers are so important is because they can reduce overall displacements and damage to structural systems that typically result from natural disasters. Ideally, investing in a damper for structural stability in buildings acts as insurance; improving the structural integrity of buildings implies that fewer repairs will need to be made in the case of a natural disaster. Essentially the damper will reduce the interstory drift of the structure which will, in return, reduce the overall displacement. Furthermore, dampers allow for yielding so that the initial stiffness and base shear of the structure are reduced. This is a result of nonlinear displacements within the system. The damper presented in this thesis is to be installed into a braced frame structure. The damper will essentially brace this frame and allow for nonlinear deformation to occur without failure of the structure. This is a result of the elasticity of the damper system.

More than one type of damper exists. The main two types are viscoelastic and hysteretic, although there are many different versions of each. A short description of each will be given now, and a more in depth definition will be given in the next section. Viscoelastic material dampers do not have linear elastic properties. In other words, the damping ratio is proportional to velocity and displacement. This differs greatly from hysteretic material dampers which rely on linear elastic material properties that generally have a yield point. Hysteretic dampers depend on the relative displacements within the damper to dissipate energy.

Relevant to the purpose of this concept is the desire of structural engineers to prevent progressive collapse. The idea is that a building may withstand one earthquake, but that one earthquake may have used up the buildings capacity. Progressive means that the building is increasingly more vulnerable to each succeeding earthquake tremor. The damper will reduce the probability of collapse in any given earthquake. This may save the building from failing. Relatively few repairs would be needed and many buildings would be saved. Progressive damage to the building would be greatly reduced. Thus, this damper would fulfill a vital need.

It might be beneficial to combine the design shown in this thesis with other collapse prevention measures. This may help the design to be more effective in more extreme cases where an earthquake may also trigger a secondary natural disaster, like a tsunami like in Northern Sumatra as discussed below. This combination of designs can be tailored to the specific problems that each region may face. Future research would need to be performed on this subject, but this would give the damper a much broader range of applicability.

1.2 Background

The need for a device such as the tire damper can clearly be seen when looking at damage from past earthquakes, especially the effect earthquakes had on poorly engineered nonductile one-to-three-story concrete buildings. These types of buildings are where this design would be implemented. Therefore a review was carried out on the effect of previous earthquakes on this type of building. The following were included: the 7.0 magnitude earthquake in Haiti on January 12, 2010; the 7.0 magnitude earthquake of Christchurch, New Zealand on September 3, 2010 with an 6.1 magnitude aftershock on February 21, 2011; the 7.6 magnitude earthquake in Costa Rica on September 5, 2012; and the 9.1 magnitude earthquake in Northern Sumatra on December 26, 2004.

1.2.1 Haiti

The January 12, 2010 earthquake with a 7.0 level magnitude was 8.1 miles deep. It was 15 miles from the nearest city, Port-Au-Prince. The devastation from this earthquake was very large as 316,000 people were killed, 300,000 were injured, and 1.3 million people were displaced from their homes. Destruction from this earthquake continued as there have been 59 aftershocks greater than a 4.5 magnitude, the largest of the aftershocks being of magnitude 6.0. While not all deaths can be prevented, it is believed that implementation of dampers would reduce the number of building collapses which is the main cause of death. In Port-Au-Prince 97,294 homes were destroyed and 188,383 were damaged.[4] Additionally, 30,000 commercial buildings were destroyed or severely damaged.[8] The need to prevent collapse of buildings is great. While the people of Haiti cannot typically afford to construct buildings that would withstand this magnitude of devastation, the design presented in this thesis gives them a valuable option which will help prevent the death toll being so high in the future.[4]

1.2.2 Christchurch, New Zealand

The September 3, 2010 earthquake had a 7.0 level magnitude, similar to the Haiti 2010 earthquake. It was 3.1 miles deep and 30 miles from the nearest city, Christchurch. This earthquake was not as deep as the one in Haiti which means it was more devastating, but it was further away from any structures. Therefore, only two people were injured from this earthquake and there were no deaths. However, on February 21, 2011 there was a 6.1 magnitude aftershock which was much more devastating. This earthquake was 3.7 miles deep and 3 miles from Christchurch, New Zealand. While the magnitude of the earthquake was not as large, it was significantly closer to structures. This greatly raised the destruction level; 185 people were killed and 1,500 were injured. While some buildings were destroyed in the original September 2010 earthquake, the number was very small compared to the 100,000 in this aftershock.[6] Once again, the death toll would probably have been substantially smaller if the buildings had dampers and were more structurally sound. It should be noted though that 110 of the deaths in this earthquake resulted from the collapse of two large office buildings.[5] This damper design would be more effective for one-to-three-story buildings as stated previously, and would not be as efficient for multiple story office buildings. However, if the smaller buildings in earthquake prone areas were implanting safe seismic designs, bigger corporations would have more incentive to take preventative measures and also implement these safe design practices.

Another important lesson from this aftershock earthquake is the idea of progressive damage that was discussed earlier in this section. Many buildings were damaged, but did not collapse, from the original September 2010 earthquake. The aftershock earthquake simply finished the destruction of the already critically damaged buildings.[5] The main goal of the damper, which is presented in this thesis is to reduce the initial earthquake damage and to reduce the progressive increase in damage. Along these lines, the Canterbury Earthquakes Royal Commission made efforts after this aftershock to improve building codes and take more preventative measures.[7] The committee made 70 recommendations, but it is up to engineers to use the recommendations in their designs. The recommendations have not yet become law. The Ministry of Business, Innovation, and Employment hopes to make amendments to the design code to improve the current lack of seismic engineering regulations. It would be desirable if all countries took these preventative measures so that lives all over the world can be spared in the future.

1.2.3 Costa Rica

The September 5, 2012 earthquake had of a 7.6 level magnitude. It was 24.9 miles deep and 6 miles from the nearest city, Hojancha. Despite the close proximity and high magnitude of this earthquake, destruction was not very significant because the earthquake was so deep. Only one person died from the earthquake, and one more died of a heart attack from the shock. Twenty were injured.[9] This earthquake was thought to be similar to the earthquake in Haiti, but the level of death and destruction was far less significant. This is because this Costa Rica earthquake was far deeper and because Costa Rica has much more effective seismic building codes.[8] This is a result of Costa Rica having a higher level of development and economic stability than neighboring countries and countries like Haiti. The reason the damper presented in this thesis is so important is because a strong economy is not required for its low cost, easily installable design.

Despite the low level of death and destruction from this earthquake, it is vital that the citizens take further preventative measures in the case of an aftershock like the one in the Christchurch, New Zealand earthquake. While damage to existing buildings was not very high, damage will still increase in the case of another earthquake. With dampers installed in Costa Rican buildings, initial damage would be even less significant and progressive damage would also be reduced.

1.2.4 Northern Sumatra

The December 26, 2004 earthquake had a 9.1 level magnitude. It was 18.6 miles deep and 250 miles from the nearest city, Banda Aceh. This earthquake introduces a completely new genre of elevated design. While this earthquake goes beyond the design presented in this thesis, it is an interesting case to look at as far as potential exceptions to the presented damper working. This earthquake was so massive that it caused a tsunami. It is the largest earthquake that the world has seen since the turn of the century in the year 1900. In the devastation of this earthquake, 227,898 people were killed and 1.7 million people were displaced from their homes. The tsunami resulting from this earthquake killed more people than any other tsunami to date. The earthquake was so powerful that it even awoke a volcano, which was spewing gas 2 days after the earthquake.[10] This earthquake gives structural engineers an example of a new world of design to consider in areas that may be prone to this level of destruction.

1.3 Applicability

A very important aspect of this design is its simplicity. It is easy to construct and is made with readily available materials. The simplicity of the damper is vital so that the design can be implemented in the maximum number of projects. When fewer materials are used the damper will cost less and the installation process will be easier.

The building structure which would typically benefit from this damper would be a nonductile concrete frame. More specifically, the building could be an unreinforced masonry infill in a concrete frame. Very often this type of building will act as a typical building with shear walls. This is a bad thing in the case of a large magnitude earthquake, if the connections between the walls and the floors are not ductile and strong. However, the earthquake resistance can be sufficient. The right balance of ductility and strength can allow for a reduction of stresses in the building and for the promotion of adequate bearing capacity.[11] This optimal balance is what the damper will provide. The tire damper was designed for a similar configuration; a diagonal braced frame.

1.4 Sustainability

The design presented in this thesis is sustainable in many ways. Most importantly, this damper may prevent building collapse. Instead of a pile of rubble, the building will still be standing. Additionally, this damper uses materials that are very unusual. This means that the demand on typical building materials will be reduced. This also adds to the sustainability of the tire damper.

Recycling of materials is also a very sustainable aspect of this damper. Used tires which would normally be disposed of and placed into landfills can instead be reused in this design for a very useful purpose. Landfills may be dangerous for the environment depending on their design. It is sustainable to reuse the tires because it will prevent the growth of tire landfills. There is an excess of millions of tires every year which means that landfills continue to grow. Landfills can create fires, spread diseases, waste acres of valuable land, and pollute the groundwater.

Another aspect of sustainability is the simplicity of the connections for the use of this damper. Usually, thousands of dollars are spent for just the connections of other dampers such as buckling restrained braces. In this case, there are pin connections which cost very little in relation to other connections. This adds greatly to the sustainability of the design.

2 LITERATURE REVIEW

2.1 Dampers

As stated in the introduction, there are two types of dampers. These two types are hysteretic and viscoelastic. Hysteretic dampers dissipate energy based on displacement and viscoelastic dampers dissipate energy based on relative displacements and relative velocities. Hysteretic dampers include: metallic yielding devices, added damping and stiffness devices, buckling restrained braces, eccentrically braced frames, base isolation, and friction dampers. Viscoelastic dampers include: viscoelastic solids and viscoelastic fluids. A description of each will be given. These dampers are built for very specific purposes and are very costly. This research is very innovative because it so greatly reduces the costs and increases the applicability of the damper.

Steel yielding devices are small and are placed into a braced frame. This damper dissipates energy as the ground motion displaces the frame in opposite directions as the earthquake runs through its different cycles of ground motion. The steel dissipates energy as it deforms through the displacement of each cycle.

Added damping and stiffness (ADAS) devices are based on the principle of material yielding. In this type of damper, triangular parallel plates made of steel are placed together so that they can bend together when they are subjected to pressure.

Buckling-restrained braces (BRB) have recently become more common. They are made of both steel and concrete. In this damper, concrete is placed around a steel center. A viscous material is placed between the steel center and the external concrete so that friction within the system is minimized.

Eccentrically braced frames are a combination of a braced frame and a moment frame. This combination is an attempt to optimally use strength and inelasticity in the design. A fuse is placed in this design between the connections. The fuse is designed to fail before the stronger parts of the frame.

Base isolators are placed underneath buildings to resist ground motions at the ground level. This type of damper is usually created from lead and rubber materials. This type of damper is ideal for large, stiff, low-rise, heavy buildings.

Friction dampers act in a way that is similar to steel yielding devices. The frame deformations cause the damper to be engaged. However, no part of the damper yields from the displacements. This device consists of small brake pad like materials which are inserted into the frame bracing. Deformation is stopped on one axis as elongation is allowed on the other.

Viscoelastic solid dampers are composed of rubber sandwiched between steel plates. The rubber is bonded to steel to prevent the device from coming apart. The deformation of the rubber dissipates energy. The level of dissipation is dependent upon the vibrational frequency, strain, and temperature.

Viscoelastic fluid dampers are composed of hydraulic pistons and lubricant. The dissipation of energy in this type of damper is achieved with the movement through the piston of a highly viscous fluid.

2.1.1 Perforated Plate Damper[3]

In his thesis Ross explores the effectiveness of a perforated steel plate damper. This damper is essentially a plate with holes. The purpose he gives for the perforations is the ability to allow higher levels of yielding. The hysteretic damper that he designed was cyclically tested and the hysteretic behavior of the damper was determined. The experimental results from his research were compared to analytical findings. The method of equivalent viscous damping was used to determine the energy dissipation of the damper. The goal of the newly designed damper is to provide nonlinear deformation in specified, pre-planned locations in the structure. The author believes that the geometry of the steel component can help control the deformation of the structure. One very interesting and applicable statement from his research is that “preliminary modeling shows how the shear stresses concentrate on the designed fuse points (nodes)” (p. 22) [3].

Several attempts were made to improve the initial design of the perforated plate damper. These improvements helped to lessen the nonlinear geometric influences, limit the tension deformation, and provide multiple stress paths to provide multiple yielding points so that yielding does not occur all at once. The goal with this perforated damper design was to have consistently elastic conditions in the exterior body of the steel plate while most of the yielding occurred in multiple stress paths that result from perforations in the center of the ring.

The damper failed with uneven cracking and twisting with the initial design. Ross[3] then put confinement plates on the damper to prevent any twisting. Failure then occurred straight across the center, right in the center of the middle row of perforations. Next, Ross added diagonal straps onto the damper. The damper then failed across the center in a rectangular shape. A fourth test was done which was the same as the first, but the out-of-plane bending was eliminated. Small cracking of the specimen was observed. The stress patterns on this testing sample are also visible. Diamond patters can be seen where the metal has been pulled in many directions. Two more tests were performed after this, both with straps and added pin connections. The second of the two was allowed to test past failure of the central plates. Tests four through six only were analyzed as the data was much more reasonable for these tests.

Through the analysis of these tests, it was found that geometric deformation was reduced, but strain hardening at the nodes was an issue. Ross also found that along with the steel plates allowing for more energy dissipation, they also provide load redundancy and delayed secondary stiffness to the system. This means that they are very valuable in adding to the initial design.

2.1.2 Preliminary Tire Damper Investigation[2]

It is important to note that this research builds off of previous work done at the University of Utah. In this previous research one specimen was tested. This specimen was constructed without reinforcement bar and rods; only duct tape, concrete, and an old tire were used. Out-of-plane buckling was not observed in the testing. Tarade[2] evaluated the data with hysteresis loops, and also showed the loop that was created at each lateral displacement. She found that the damping system began to fail at 2.2 and 2.5 inches of displacement; the hysteresis curves were no longer smooth. Spikes could be seen in the hysteresis loops at these displacements. The author credits these spikes to the failure of the concrete and reinforcement bar, and states that after this failure the rubber and steel belting from the tire is what dissipates the energy of the oscillating displacement. This resulted in hysteresis loop behavior. The author discovered that failure occurred in the steel belts of the tire and not in the steel beading around the inner rim of the tire. Also, failure was seen in the steel plate pin connections. She found the maximum compression cycle failure to occur at 2.219 inches of displacement and 42.085 kips. The maximum compression cycle failure occurred at 2.08 inches of displacement and 34.35 kips.

2.1.3 Rubber Base Isolator

It is important to look at research that others have completed on the subject of rubber dampers. The use of rubber in base isolators and bearings has been described by Kelly.[12] It was suggested that the rubber tire damper design introduced in this thesis could be combined with rubber base isolators to make it even more effective. Kelly also had this thought, and experimented with it. However, his experimental results show that this would probably not work. An explanation of the results he found in this experiment is provided below:

> The test results showed that when additional damping devices were added to the isolation system, the increased damping did not always lead to decreased response of the models, but induced accelerations in higher modes of the structures. It became clear that the best way to increase damping is to provide it in the rubber compound itself and that a high level of damping is unnecessary and can be detrimental.[12]

Thus, we see that the combination of a rubber damper and a rubber base isolator may not be favorable. The quality of the rubber becomes pertinent for the use of the rubber in base isolation. We also see from this statement the dangers of making the structure too flexible and insufficiently strong. The displacement of a system of this nature would be detrimentally large. A base isolator design is typically used for large buildings that are rigid and not ductile.

3 THE TIRE DAMPER CONCEPT

3.1 Overview

Physical experimental testing must be implemented to explore the behavior of a new system. Ideally the results will prove the usefulness and effectiveness of the damper design. This testing was done using a 120 kip tension actuator. The frame in which the specimen was installed was intentionally made to fit real life specifications as far as size and installation. The testing continued until failure occurred in the nodes of the testing apparatus as stated above. The tension in the cross bracing system was then released and the testing specimen was removed so that it could be inspected. The tires were found to deform in an elongated oval shape.

In designing this damper, tire dissection became important. The dissection allowed for the tire to be dismembered and inspected. This allowed for a better understanding of the damper failure. The different portions of the tire which the reader is most likely not familiar with are discussed and pictured below. First is the bead of the tire which consists of 16 metal wires. These wires wrap around the inner diameter of the tire to give it added strength and keep it together. This can be seen in **Figure 1**.

Figure 1 - Tire Bead

The picture in **Figure 2** shows where the steel belts begin in relation to the bead. The steel belts are essentially a mesh in the tire. This mesh is just inside the tread area, indented about 1/2 an inch on both sides from where the tread begins.

Figure 3 shows a 90 degree view of the perpendicular wire meshing, which is known as the steel belts. This picture shows very well how the steel belts are woven together.

The beading wires are shown in **Figure 4**. These are the wires mentioned above that run through the inner diameter of the tire.

A cross section of the tire is shown in **Figure 5**. The dots along the top are made of a fabric material and are called polyester cords. Underneath these dots the steel belts can again be seen.

3.2 Material Details

The main attraction to this damper design is its simplicity. The design requires only the following materials: four 6-inch square ½ inch thick plates, four I-bolts, and placement of concrete which is done in two or three different stages, a 15 inch tire, and reinforcing bars within the concrete or diagonal cross tie rods. The I-bolts have a 9 inch shank, a 2 inch inner diameter, a 5/8 inch thread, and a 1 inch shaft. The concrete mix design is very simple and basic; it is shown in **Table 1**.

3939 Duct Tape was used to wrap the tire. This helps to prevent the concrete from falling out of the damper as it spalls and cracks. This specific duct tape has a tensile strength of 25 lb/inch width. This means that a width of 1.9 inches will lead to the duct

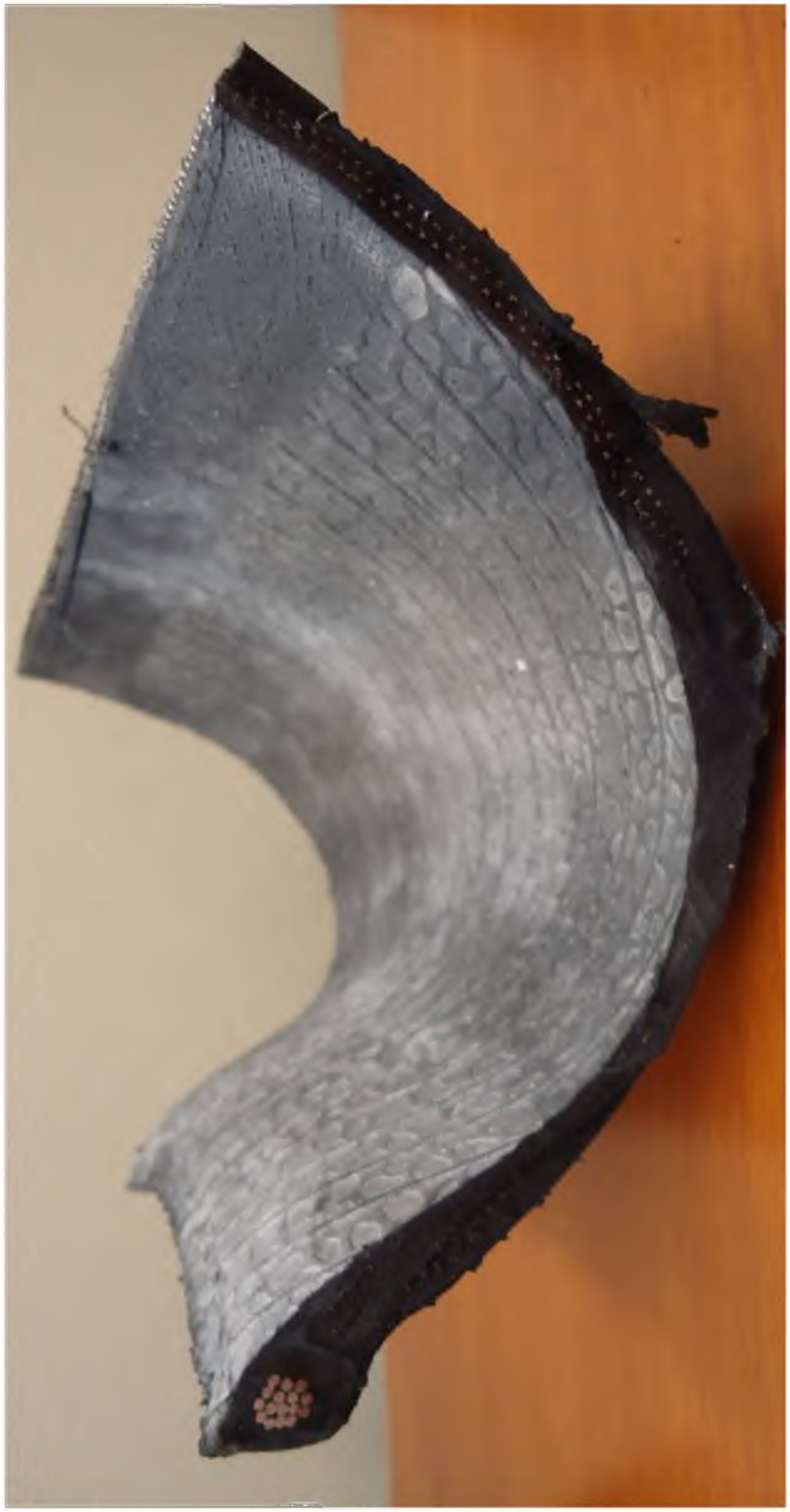


Figure 2 - Steel Belts Location

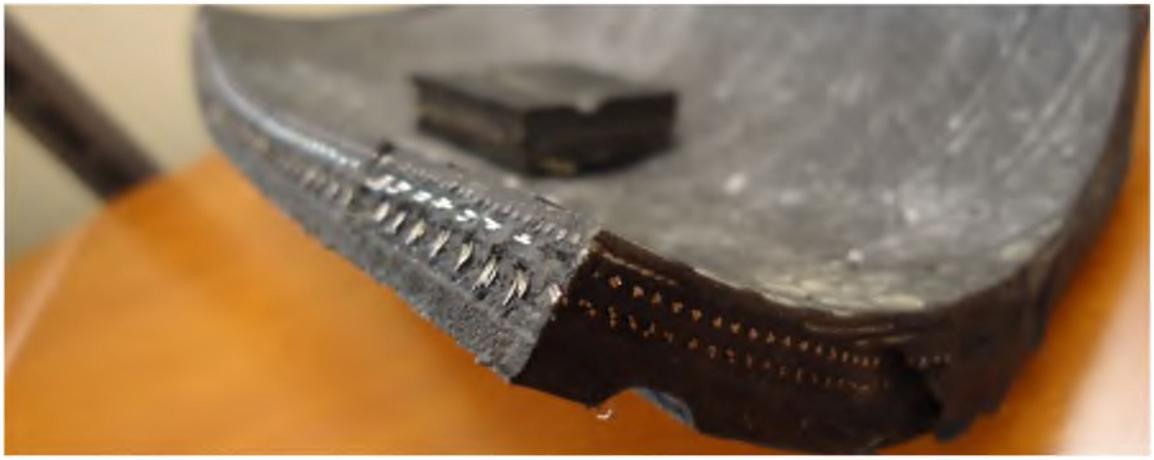


Figure 3 - Steel Belts Perpendicular View

Figure 4 - Beading Wires

Figure 5 - Steel Belts Strip

Table 1 – Concrete Mix Design

Material	Weight (pounds)
Coarse Aggregate	61.2
Fine Aggregate	41.4
Cement	18.8
Air Entrainer (MBVR)	5.0

tape having strength of 47 pounds. Also, this specific roll of duct tape can elongate 14% before failure occurs. The roll of duct tape was wrapped around the tire simply to help prevent pieces from dropping out during testing. It is assumed that the strength of the duct tape is negligible because it was not preloaded and because of its low Modulus of elasticity.[1]

4 EXPERIMENTAL WORK

4.1 Overview

An experimental testing program was conducted to explore the behavior of the tire damper when subjected to cyclic loading. A diagonally braced frame configuration was used in this research. It is important to note that the analysis of the testing does not include the frame or the connections which were used in the testing configuration. The two different damper designs were created and tested in this frame so that a more optimal design could be chosen. The difference between the two damper designs which were used in each of the four tests is illustrated in **Table 2**. A diagram which further explains the installation process of the rods in the third and fourth tests is shown in **Figure 6**.

It was intended in this design that the initial circular shape of the tire would allow for a great reduction in nonlinear geometric influences, and that the stresses would be spread out evenly in the damper rather than being concentrated in one place.

4.1.1 Testing Apparatus

It is important that the testing operation be used multiple times with no alterations. Any alterations will cause experimental error in the results. Additionally, it is

Table 2 – Comparison of Testing Designs

	15" Tire Filled with Concrete	Two Loops of Reinforcement Bar in Concrete	Diagonal Cross Ties/Rods	Duct Tape	Pin Connections
Tests One & Two	√	√	------	√	√
Tests Three & Four	√	------	√	√	√

important that the frame can be reset to initial conditions; no yielding occurs in the testing apparatus. This means that the frame has no inelastic deformations and has little elastic deformation because of the area of the steel members, while the bulk of the deformations occur within the damper. Pin connections are installed to connect the damper to the frame. These pin connections can be seen in the collage shown in **Figure 7**.

A full scale sway frame was constructed for this research. In this frame, lateral movement is induced in the structural system by the horizontal actuator which is installed parallel to the top frame member. An actuator is a hydraulic fluid motor which simulates the displacement cycles. This lateral displacement creates alternating tension forces which act on the damper. The lateral displacement can reach up to 7 inches in each direction. This is a great deal of displacement in a building; ideally the deformation would be much smaller than this in a real life building. The picture in **Figure 8** was taken after the installation of the damper and before the commencement of the testing.

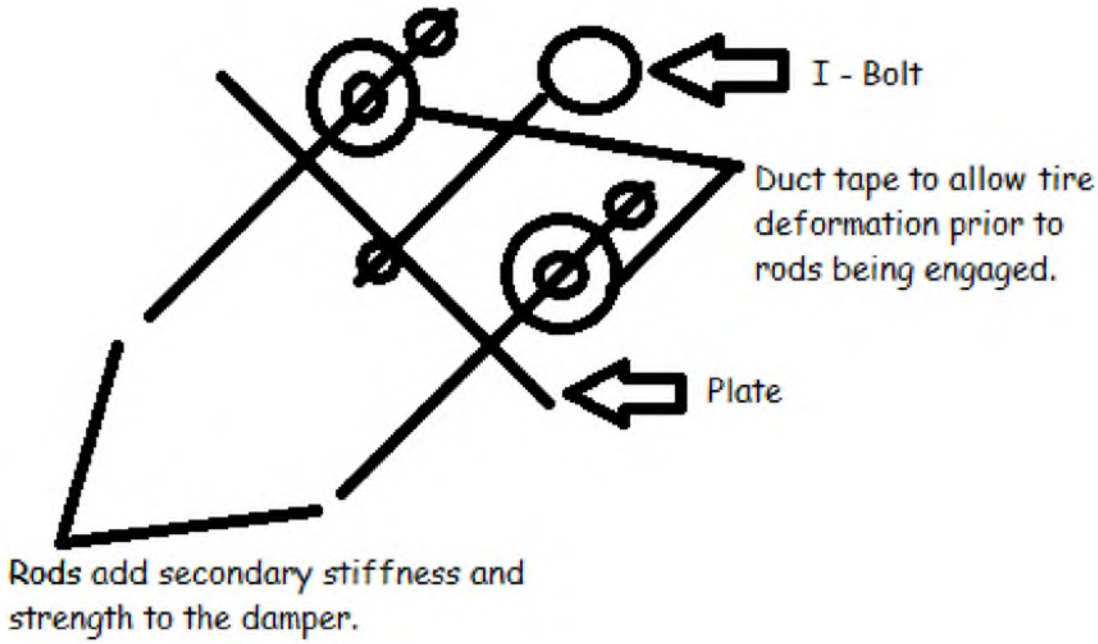


Figure 6 – Rod Configuration

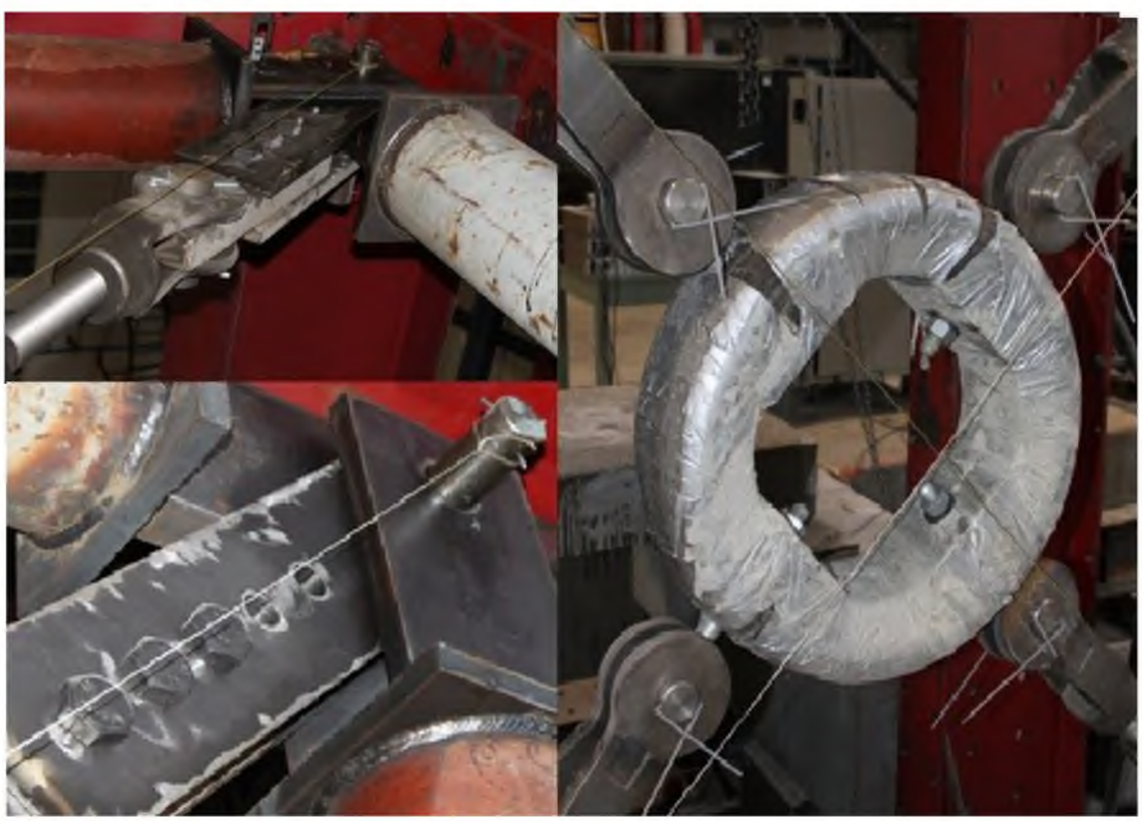


Figure 7 – Pin Connections Collage

Figure 8 – Test Frame

4.1.2 Instrumentation

The instrumentation in this research consisted of linear variable differential transformers (LVDT's). These LVDT's were used to measure the lateral displacement of the tension braces within the frame as the testing was conducted. Also, a load cell was used to measure the actuator force.

4.1.3 Testing Protocol

The tire was stretched in two directions with controlled displacement using the cyclic testing frame shown in **Figure 8**. Values started at 0.2 inches of displacement and continued in increments of 0.2 inches until failure was reached. The displacement was achieved with the use of a hydraulic ram. This equipment was designed to directly output displacement and force values in relation to time into a computer spreadsheet. The information from the spreadsheet was utilized to create the hysteresis loops in this section and graphs shown in **section 5** of this report.

4.2 Experimental Results

4.2.1 Discussion of Experimental Results

Figures 9, **10**, **11**, **and 12** show the hysteresis loops from each of the four tests. These loops are LVDT displacement on the x-axis versus actuator force on the y-axis. The loops are also graphed individually in **Appendix A**. In these graphs three different sections can be seen on displacement axis. These three sections will be labeled as follows on each of the four graphs: 1 Linear Elastic, 2 Plastic, and 3 Residual. The first

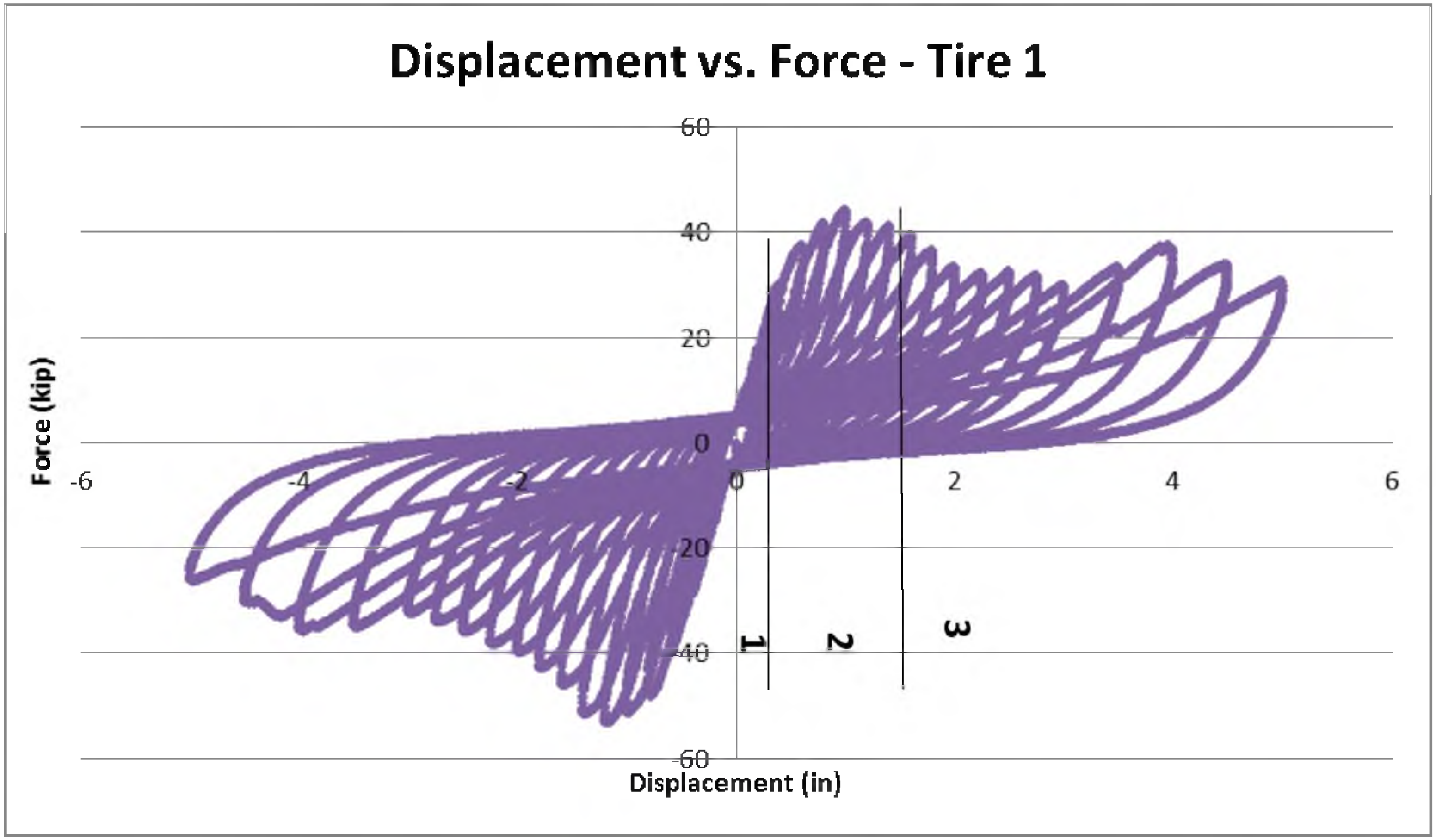


Figure 9 – Hysteretic Loops for Test One

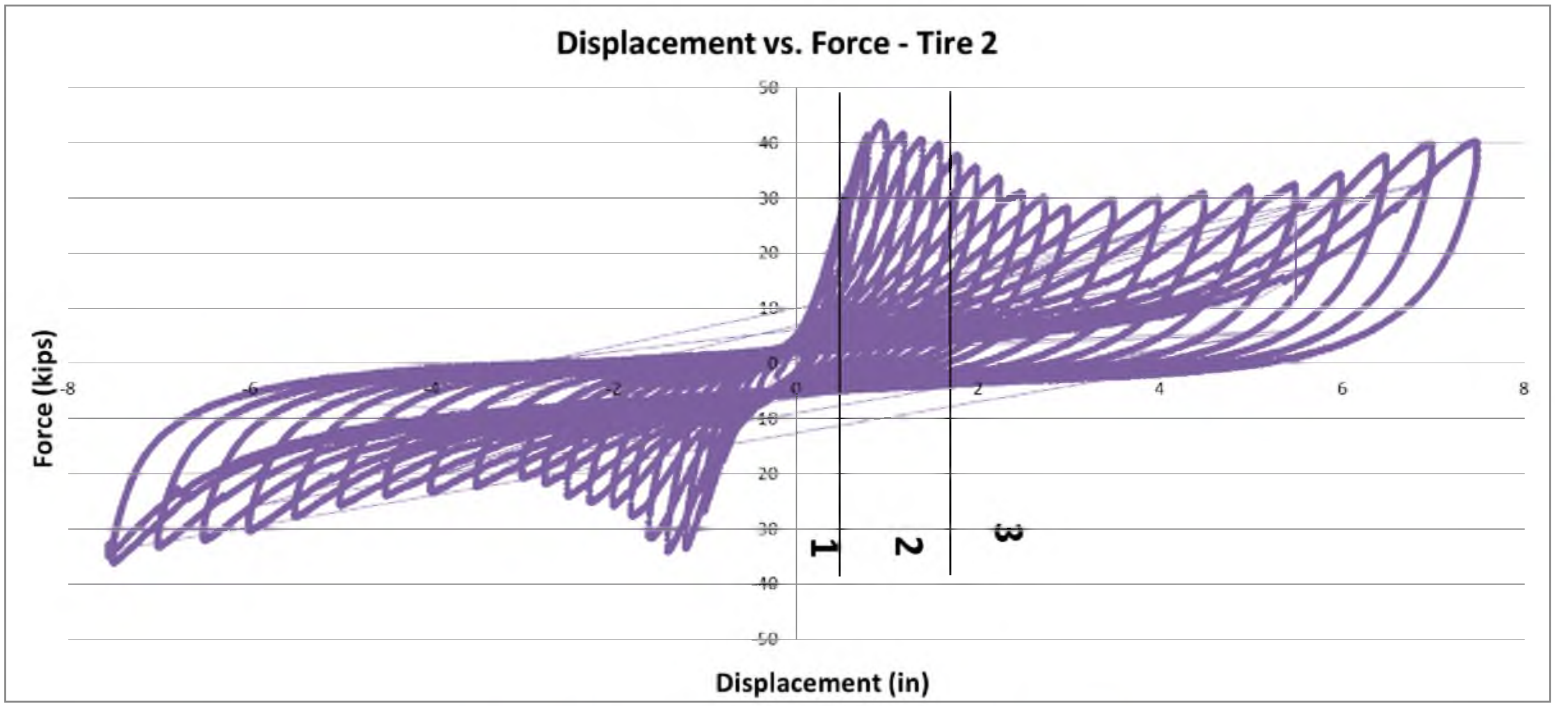


Figure 10 – Hysteretic Loops for Test Two

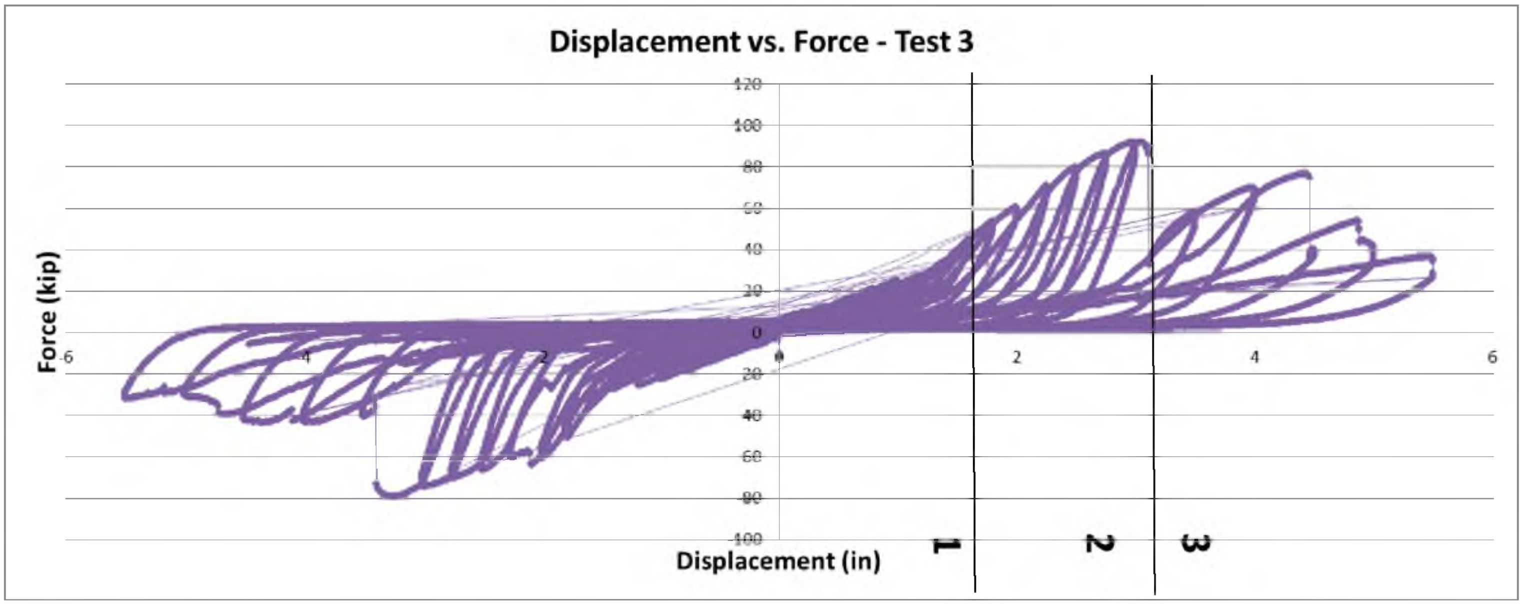


Figure 11 – Hysteretic Loops for Test Three

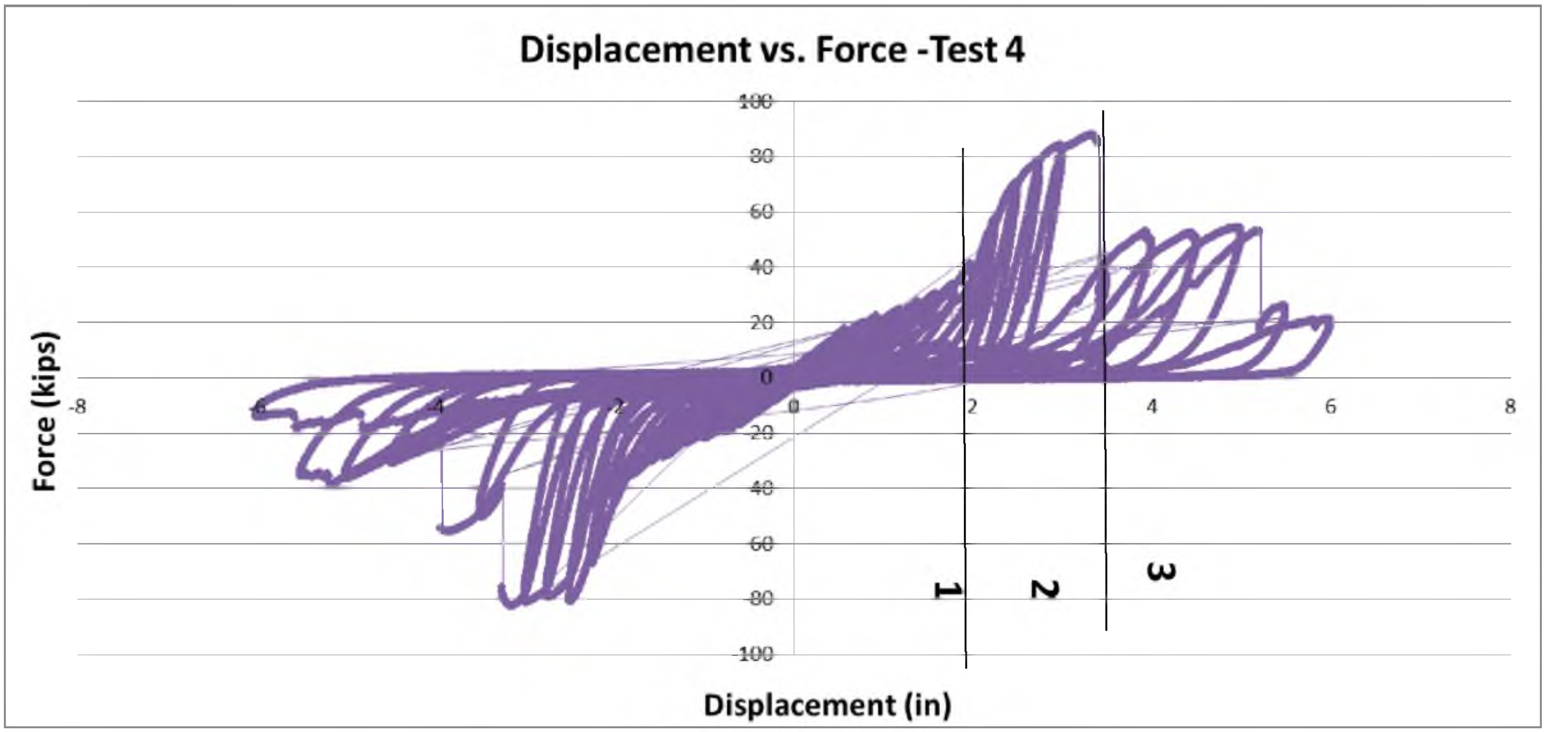


Figure 12 – Hysteretic Loops for Test Four

section can be seen starting from the y-axis where the looping is flat. This section is where the deformation of the tire can be seen. The next section is where the forces are at a maximum. This section is the residual part of the looping where the linear deformation of the dampers reinforcement (rods/rebar) is seen. The next section is where the nonlinear deformation of the reinforcement is seen. It should be noted that the residual forces for each test are considered as the point at which the maximum forces quickly drop, remain steady, and then grow again. The residual of the four tests will be compared in **section 5**.

4.2.2 Tire Damper Failure Modes

A depiction of the maximum elongation can be seen in **Figures 13**, **14**, **15**, **and 16** for each of the four tests.

A great deal of energy is dissipated as the concrete begins to crush, spall, and crack in these maximum elongations. The duct tape on the damper helps to prolong the strength of the damper by holding the fractured concrete in the tire. As the deformation increases the duct tape tears and no longer helps the concrete to retain its strength. The failure of the concrete is shown at two different stages in **Figure 17**, where the concrete has crumbled and fallen and the reinforcement bar is exposed. Note that this picture was taken after the duct tape was removed from the area.

Next, the rebar inside the broken concrete takes the majority of the stress within the damper. Reinforcement bars are shown below in **Figure 18**. Note that the ends of the rebar shown were not fractures, but are the ends of the spiral hoops.

Figure 13 - Test One Maximum Elongation

Figure 14 - Test Two Maximum Elongation

Figure 15 - Test Three Maximum Elongation

Figure 16 - Test Four Maximum Elongation

Figure 17 – Concrete Failure

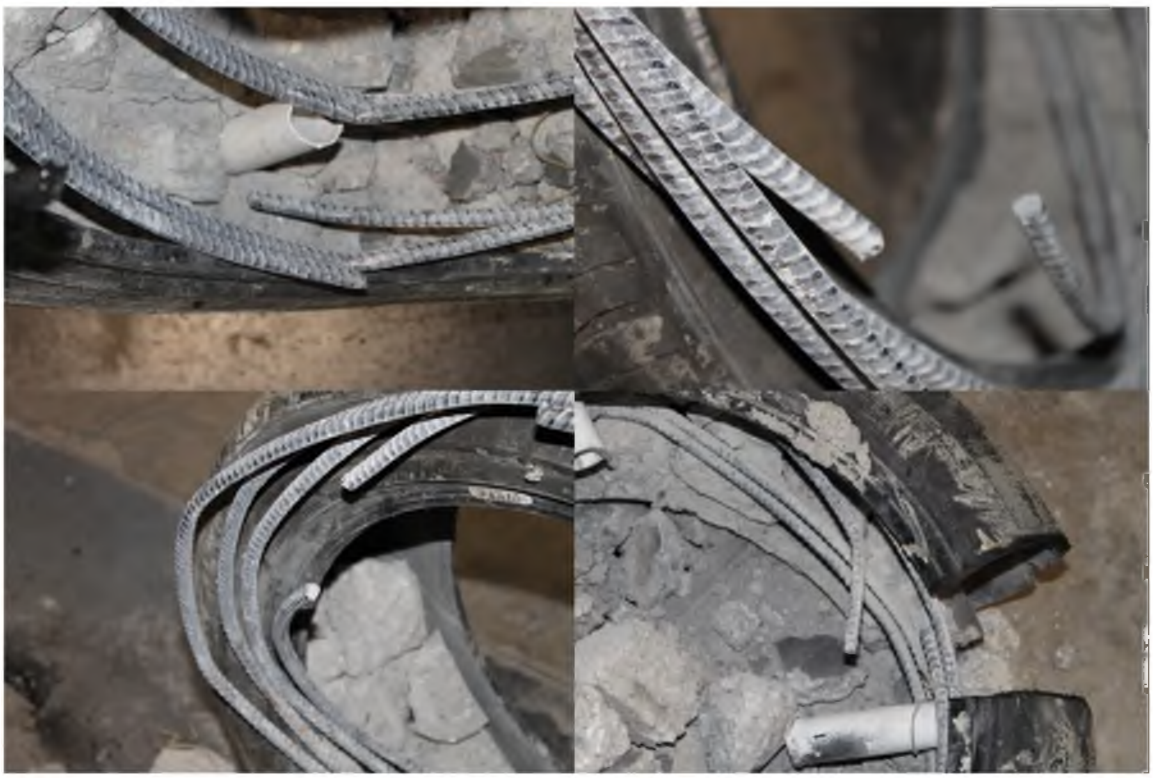


Figure 18 – Reinforcement Bars

Two of the four tests also included rods, as shown in **Figure 19**. When these rods fail, a very loud noise is heard as the metal elongates and buckles. The progressive failure of the rods can be seen in the collage in **Figure 20**.

The progressive failure of the rods from the fourth test can be seen in **Figure 21**.

Once the rod fails the rubber begins to tear, especially around the four I-bolt connections which secure the tire to the frame in tension. The failure of the rubber and steel belts within the rubber can be seen in the pictures shown in **Figure 22**.

As the deformation of the reinforcement bar, rubber from the tire, and the steel belts within the tire continues, an increasingly high amount of energy is dissipated. Failure was achieved when the loading capacity of the damper began to sharply decrease due to the fatigue of the system. The plates at these connections caused tapered wedge failure at the four connections. This failure is shown in **Figure 23**.

In the second rod test the ultimate failure was even more pronounced, as seen in **Figure 24**. This failure occurred when the deformations were beyond 5 inches. Note that the duct tape was again removed from the tire in the affected areas before this picture was taken.

4.3 Hysteretic Performance and Stiffness Degradation

There are many material behaviors that can cause uncharacteristic changes to hysteretic loops. These behaviors which will be discussed are pinching, ductility, cyclic creep, cyclic softening, and cyclic hardening. All of these behaviors affect the shape of

Figure 19 – Tests Three and Four Rods

Figure 20 – Test Three Rod Failure

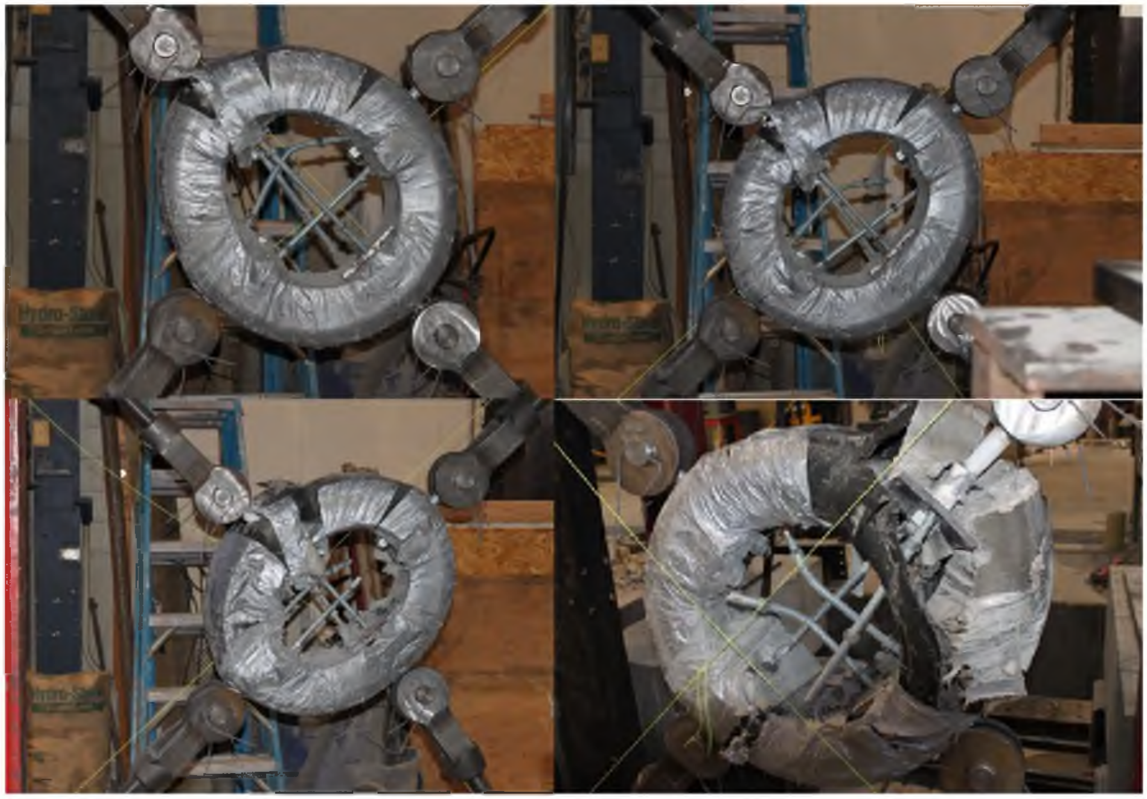


Figure 21 – Test Four Rod Failure

Figure 22 – Rubber and Steel Belt Failure

Figure 23 – Wedge Failure in Test Three

Figure 24 – Wedge Failure in Test Four

the curves and are a detriment to the ideal, smooth loops that might be seen in a textbook for an all-steel specimen.

- Pinching, as it will be seen, has a great effect on this damper. This behavior is detrimental to the purpose of the damper as it decreases the potential dissipation of energy. Pinching results from the yielding of the different components in the damper systems, and results in narrow loops.
- Ductility is a behavioral result due to yielding of the system. It is defined as the ratio of the inelastic displacement to the elastic displacement.
- Cyclic creep is the behavior of the damper in which plastic deformation increases with each cycle without the displacement returning to its starting point. The repeated cyclic testing causes the materials to progressively be stressed beyond their yield point. This progressive damage accumulates.
- Cyclic softening involves the stiffness of the damping system as it changes with time. As the test progresses through its different cycles, the stiffness will decrease. The hysteretic loop size increases, however the damper itself is losing its strength. The damper is then so flexible that the reinforcement bar for the first two tests or the rods for the third and fourth tests kick in.
- Cyclic hardening also involves the dampers stiffness. However in this case, the stiffness of the system is increasing instead of becoming weaker, because of strain hardening. When this occurs, failure is imminent.

4.4 Energy Dissipation

The energy dissipation is defined by the enclosed area of each loop. This is shown as E_D in each of the four tables in the data analysis section of this thesis. The larger the area of a hysteresis loop, the bigger energy dissipation by the damper. This will in turn increase the efficiency of the damping ratio; the higher this ratio is the more effective the system is. As the test continues, both the displacement and the force that the damper is subjected to will increase. This increase can also be clearly seen in the tables which summarize the data analysis results for each of the four tests. The stiffness of the damper as it changes with time is also very important.

5 ANALYSIS OF DATA

5.1 Computational Analysis

It should be stated that in the analysis of the data, a reading with positive displacement elongates with the top right side of the tire up and the bottom left side down, and a reading with negative displacement elongates with the with the top left side of the tire up and the bottom right side of the tire down when looking at **Figures 13, 14, 15 and 16** in the previous section. The tire goes through cyclic internal forces as these maximum elongation deformations occur. A detailed description of these forces is shown in **Figure 25**.

It can be seen in the diagram shown in **Figure 25** that the beading, rebar, and tire rubber all counteract the opposing force that is acting on the plate. The rebar acts as the top steel in a cantilever. The wedge failure area which is seen later in the experimental work of this design can be seen in the portion of the concrete around the plate that has no shear stress. There is a shearing force which separates the area of concrete that has no shear stress and the area of concrete that has shear stress. The forces in the tire which are shown on the diagram can be shown in equation form as:

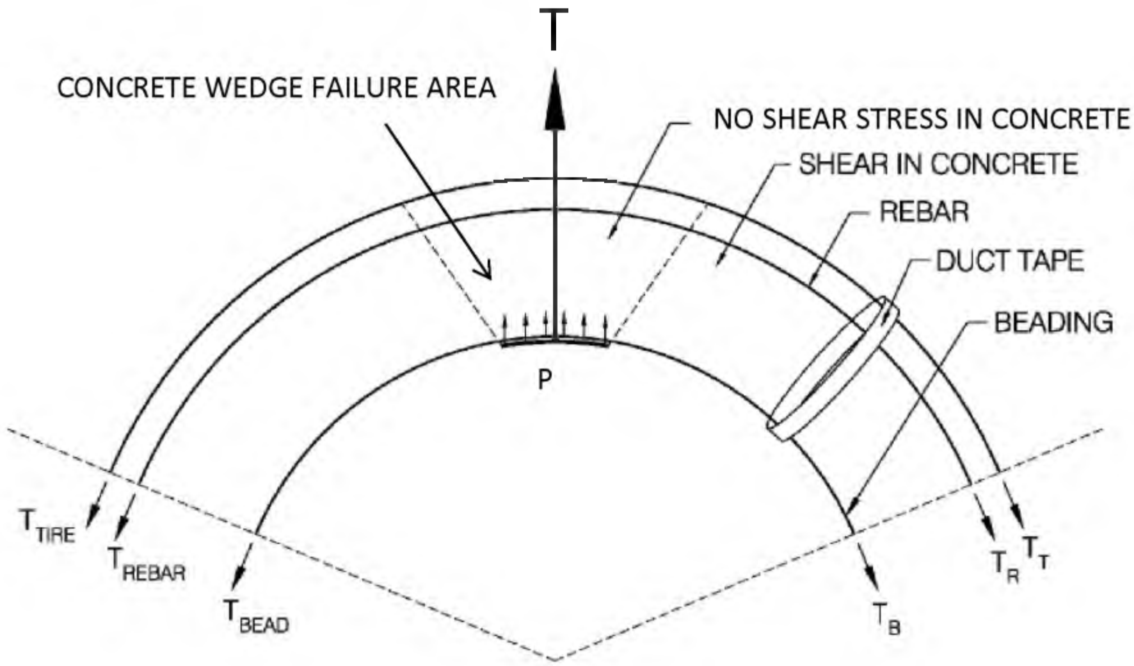


Figure 25 – Internal Forces Diagram

$$T = PA = \sum(2T_T + 2T_B + 2T_R)$$

where P = The pressure on the plate,

A= The area of the plate,

$T_R = A_S*F_Y$,

A_S = Area of steel in the reinforcement bar,

and F_Y = Force on the reinforcement bar.

5.2 Analysis Results

It is important to run multiple tests with variations so that the improvements can be easily seen. In this research two tests of two different kinds were conducted. Tests One and Two have a concrete filled tire with reinforcement bar inside and duct tape wrapped around the tire. Tests Three and Four have the same configuration without reinforcement bars inside, but rods were added as shown in **Figure 19**. The following are the results, description, and analysis for each test.

The main objective of the experimental testing was to acquire data that will allow for the characterization of the hysteric behavior of the damper. This characterization of the data was performed by the following steps:

1. Positive and negative stiffness for each loop (slope of displacement and corresponding force).
2. Damping energy (area) for each loop.
3. Elastic energy (triangular positive stiffness area) for each loop.
4. Damping ratio for each loop ($\varsigma = [E_D/(4\pi * E_{so})]$).

The damping ratio will prove the success of the design, as it allows for a comparison to modern dampers.

In **Table 3** the analysis of Test One is shown. The average damping ratio for Test One was found to be 0.12. This excludes the value for loop 1 because the light loading at this point in the test made the data unreliable.

In **Table 4** the analysis of Test Two is shown. The average damping ratio for this test was found to be 0.10. This excludes the value for loop 1 because the light loading at this point in the test made the data unreliable. Hysteresis loops labeled as “BAD” were unusable.

Table 3 – Test One Analysis Results

Loop #	Damping Energy E_D (kip-in)	Displace -ment k+ve (in)	Stiffness, k+ve (kip-in)	Displace -ment k-ve (in)	Stiffness, k-ve (kip-in)	Elastic Energy E_{SO} (kip-in)	Damping Ratio
Loop 1	3.37	0.20	90.05	0.20	75.73	1.73	0.16
Loop 2	8.17	0.39	77.42	0.39	72.21	5.85	0.11
Loop 3	14.42	0.58	63.33	0.59	67.08	10.76	0.11
Loop 4	20.74	0.78	52.68	0.78	61.48	15.99	0.10
Loop 5	26.52	0.97	44.99	0.97	52.45	21.10	0.10
Loop 6	32.34	1.17	35.46	1.17	45.43	24.19	0.11
Loop 7	38.57	1.36	29.62	1.36	37.79	27.35	0.11
Loop 8	43.90	1.57	24.79	1.55	29.65	30.52	0.11
Loop 9	47.95	1.76	20.28	1.75	24.30	31.37	0.12
Loop 10	49.95	1.95	16.83	1.97	20.17	32.06	0.12
Loop 11	57.05	2.19	14.31	2.19	17.39	34.19	0.13
Loop 12	61.14	2.44	12.90	2.45	14.56	38.27	0.13
Loop 13	68.60	2.70	11.51	2.65	12.66	41.83	0.13
Loop 14	73.09	2.94	9.95	2.90	10.94	43.01	0.14
Loop 15	90.03	3.39	9.45	3.43	10.09	54.44	0.13
Loop 16	109.37	3.85	9.51	3.90	8.97	70.51	0.12
Loop 17	119.07	4.39	7.55	4.40	6.88	72.74	0.13
Loop 18	108.72	4.91	6.08	4.88	5.25	73.26	0.12

***Table 4* – Test Two Analysis Results**

Loop #	Damping Energy, ED (kip-in)	Displacement k+ve (in)	Stiffness, k+ve (kip-in)	Displacement k-ve (in)	Stiffness, k-ve (kip-in)	Elastic Energy Eso (kip-in)	Damping Ratio
Loop 1	1.76	0.20	48.60	0.20	27.55	0.95	0.15
Loop 2	4.54	0.39	51.22	0.40	19.58	3.91	0.09
Loop 3	8.29	0.59	53.68	0.59	18.43	9.31	0.07
Loop 4	13.74	0.78	52.18	0.78	21.93	15.91	0.07
Loop 5	22.19	0.97	44.84	0.97	26.56	21.01	0.08
Loop 6	27.24	1.18	35.19	1.18	28.03	24.41	0.09
Loop 7	22.61	0.97	44.85	0.98	26.60	21.01	0.09
Loop 8	26.86	1.18	35.05	1.18	28.02	24.52	0.09
Loop 9	32.89	1.37	29.32	1.36	24.68	27.51	0.10
Loop 10	34.87	1.36	29.49	1.57	20.23	27.44	0.10
Loop 11	38.43	1.56	25.09	1.57	20.27	30.53	0.10
Loop 12	38.79	1.56	25.15	1.76	15.64	30.72	0.10
Loop 13	40.93	1.76	21.23	1.76	15.68	32.89	0.10
Loop 14	41.08	1.96	17.99	1.96	13.10	34.45	0.09
Loop 15	43.52	1.95	18.02	1.96	12.98	34.12	0.10
Loop 16	44.96	2.19	15.15	2.19	11.32	36.45	0.10
Loop 17	47.99	2.21	15.07	2.19	11.35	36.74	0.10
Loop 18	44.45	2.18	12.47	2.45	9.69	29.49	0.12
Loop 19	51.98	2.44	12.51	2.45	9.67	37.24	0.11
Loop 20	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 21	54.04	2.68	11.04	2.69	8.02	39.52	0.11
Loop 22	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 23	58.73	2.92	9.47	2.96	6.93	40.50	0.12
Loop 24	55.44	2.94	9.40	2.95	6.11	40.53	0.11
Loop 25	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 26	71.05	3.40	8.50	3.42	6.35	49.15	0.12
Loop 27	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 28	84.63	3.91	7.50	3.91	5.84	57.40	0.12
Loop 29	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 30	95.56	4.41	6.84	4.42	5.35	66.40	0.11
Loop 31	96.56	4.46	6.73	4.92	5.13	66.94	0.11
Loop 32	103.01	4.92	6.34	4.88	5.09	76.73	0.11
Loop 33	117.50	5.40	5.84	5.37	5.03	85.27	0.11
Loop 34	123.30	5.91	5.68	5.87	5.00	99.23	0.10
Loop 35	131.04	5.89	5.66	6.40	4.91	98.09	0.11
Loop 36	133.39	6.40	5.72	6.86	4.65	117.12	0.09
Loop 37	148.33	6.93	5.69	7.42	4.77	136.62	0.09
Loop 38	156.66	7.35	5.33	7.49	4.58	144.09	0.09

In **Table 5** the analysis of Test Three is shown. The average damping ratio for this test was found to be 0.08. Hysteresis loops labeled as “BAD” were unusable due to the breaking of materials within the damper.

In **Table 6** the analysis of Test Four is shown. The average damping ratio for this test was found to be 0.10. This excludes the value for loop 2 because the light loading at this point in the test made the data unreliable. Hysteresis loops labeled as “BAD” were unusable due to the breaking of materials within the damper.

Figures 26 – 29 show the positive stiffness of the damper graphed with the displacement of the system, the negative stiffness of the damper graphed with the displacement of the system, the damping energy of the damper graphed with the displacement of the system, and the damping ratio of the damper graphed with the displacement of the system for Test One. **Figures 30 – 33** show the same graphs for Test Two. **Figures 34 – 37** show the same graphs for Test Three. **Figures 38 – 41** show the same graphs for Test Four. An explanation of these results will be given in **section 5.3**.

5.3 Discussion of Analytical Results

It can be seen in the hysteretic looping for each test that there are many irregular loops. This is especially seen in the last two tests that had the rods instead of the reinforcement bar. The jumps in data caused some of these loops to not close. Therefore, these loops were left out of the analysis and labeled “BAD” on the tables which show the result of the data analysis. These jumps in force and displacement are attributed to breaking of concrete, steel, rubber, etc. The first test was the most well

Table 5 – Test Three Analysis Results

Loop #	Damping Energy, E_D (kip-in)	Displace-ment k+ve (in)	Stiffness, k+ve (kip-in)	Displace-ment k-ve (in)	Stiffness, k-ve (kip-in)	Elastic Energy E_{SO} (kip-in)	Damping Ratio
Loop 1	1.96	0.20	47.17	0.20	32.04	0.93	0.17
Loop 2	4.75	0.39	31.56	0.40	26.10	2.44	0.15
Loop 3	7.63	0.58	28.07	0.59	24.65	4.73	0.13
Loop 4	11.07	0.79	27.12	0.79	23.74	8.35	0.11
Loop 5	14.27	0.98	25.43	0.98	22.71	12.28	0.09
Loop 6	20.08	1.17	22.97	1.14	21.73	15.72	0.10
Loop 7	14.15	0.98	25.42	0.98	22.76	12.20	0.09
Loop 8	19.11	1.17	23.00	1.17	21.71	15.62	0.10
Loop 9	23.98	1.37	24.72	1.36	19.44	23.17	0.08
Loop 10	23.53	1.37	24.72	1.56	22.26	23.26	0.08
Loop 11	29.77	1.56	27.93	1.57	22.59	34.18	0.07
Loop 12	32.72	1.61	27.30	1.75	27.97	35.20	0.07
Loop 13	36.65	1.77	29.92	1.74	27.63	46.75	0.06
Loop 14	39.28	1.94	30.40	1.95	30.07	57.39	0.05
Loop 15	43.86	1.94	30.36	1.96	30.08	57.20	0.06
Loop 16	56.77	2.19	30.82	2.20	26.92	73.91	0.06
Loop 17	61.92	2.21	31.19	2.18	26.87	76.17	0.06
Loop 18	50.71	2.20	27.60	2.44	26.64	66.78	0.06
Loop 19	50.64	2.45	32.02	2.44	26.64	95.72	0.04
Loop 20	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 21	70.48	2.68	31.87	2.70	25.74	114.44	0.05
Loop 22	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 23	76.68	2.95	31.09	2.99	24.66	135.27	0.05
Loop 24	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 25	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 26	108.30	3.91	17.65	3.90	11.04	134.93	0.06
Loop 27	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 28	135.30	4.36	17.43	4.43	9.60	165.66	0.06
Loop 29	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 30	136.62	4.76	10.96	4.52	8.44	124.11	0.09
Loop 31	141.30	5.50	6.54	5.39	5.75	98.85	0.11
Loop 32	BAD	BAD	BAD	BAD	BAD	BAD	BAD

Table 6 – Test Four Analysis Results

Loop #	Damping Energy, E_D (kip-in)	Displace-ment k+ve (in)	Stiffness, k+ve (kip-in)	Displace-ment k-ve (in)	Stiffness, k-ve (kip-in)	Elastic Energy E_{so} (kip-in)	Damping Ratio
Loop 1	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 2	2.72	0.20	41.66	0.40	31.43	0.81	0.27
Loop 3	5.62	0.39	32.57	0.60	27.97	2.50	0.18
Loop 4	9.60	0.58	27.94	0.79	24.07	4.72	0.16
Loop 5	13.08	0.77	25.79	0.98	22.15	7.65	0.14
Loop 6	18.37	0.98	21.49	1.18	19.95	10.39	0.14
Loop 7	16.44	1.17	20.90	0.99	21.21	14.30	0.09
Loop 8	17.65	0.98	21.54	1.20	19.76	10.34	0.14
Loop 9	21.67	1.17	20.91	1.39	20.07	14.31	0.12
Loop 10	24.20	1.38	19.81	1.59	19.02	18.81	0.10
Loop 11	26.61	1.37	19.85	1.57	19.09	18.68	0.11
Loop 12	32.27	1.60	18.32	1.77	19.46	23.36	0.11
Loop 13	32.67	1.57	19.16	1.78	19.47	23.53	0.11
Loop 14	37.67	1.76	18.99	1.97	22.18	29.55	0.10
Loop 15	36.85	1.95	20.57	1.98	22.51	39.07	0.08
Loop 16	49.08	1.94	20.46	2.23	29.54	38.62	0.10
Loop 17	45.22	2.23	25.13	2.22	29.37	62.48	0.06
Loop 18	58.14	2.21	24.17	2.44	32.50	58.76	0.08
Loop 19	47.64	2.21	21.98	2.46	32.52	53.52	0.07
Loop 20	67.58	2.47	28.29	2.73	29.04	86.16	0.06
Loop 21	57.15	2.45	28.22	2.73	29.03	84.84	0.05
Loop 22	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 23	68.17	2.71	28.60	2.97	27.26	105.26	0.05
Loop 24	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 25	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 26	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 27	75.44	3.87	13.29	3.87	14.39	99.25	0.06
Loop 28	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 29	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 30	81.78	4.37	11.82	4.44	6.84	112.74	0.06
Loop 31	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 32	93.60	4.87	11.06	4.95	7.24	130.91	0.06
Loop 33	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 34	BAD	BAD	BAD	BAD	BAD	BAD	BAD
Loop 35	BAD	BAD	BAD	BAD	BAD	BAD	BAD

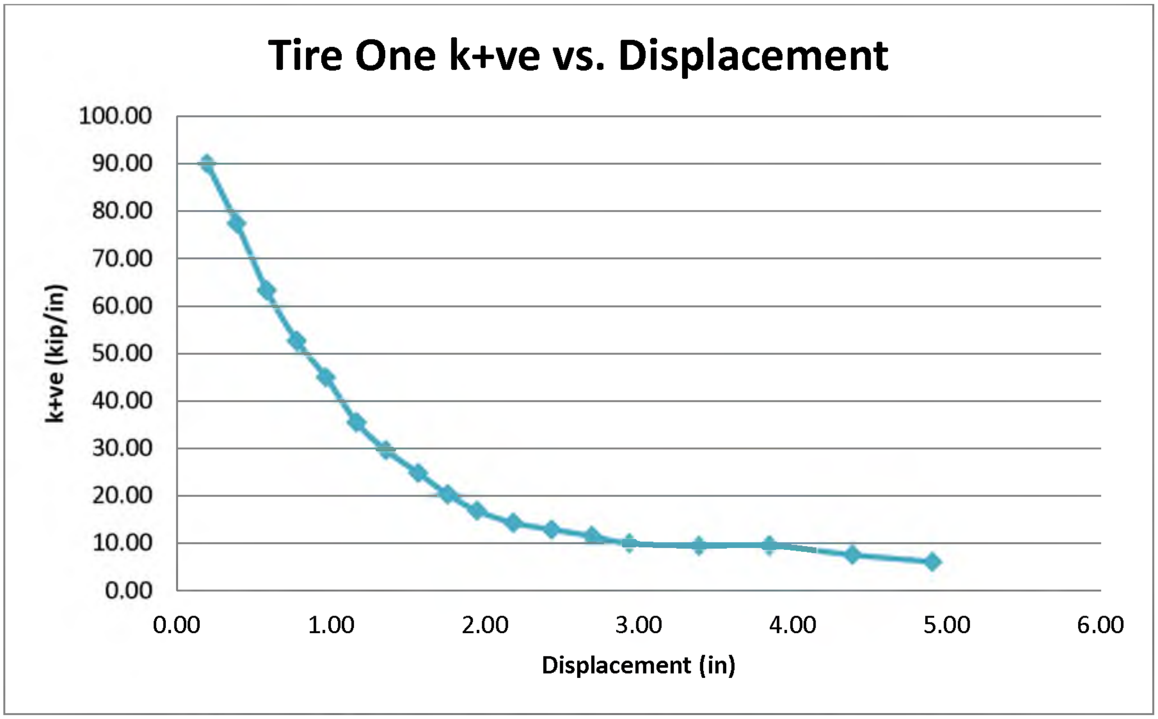


Figure 26 – Test One Positive Stiffness vs. Displacement

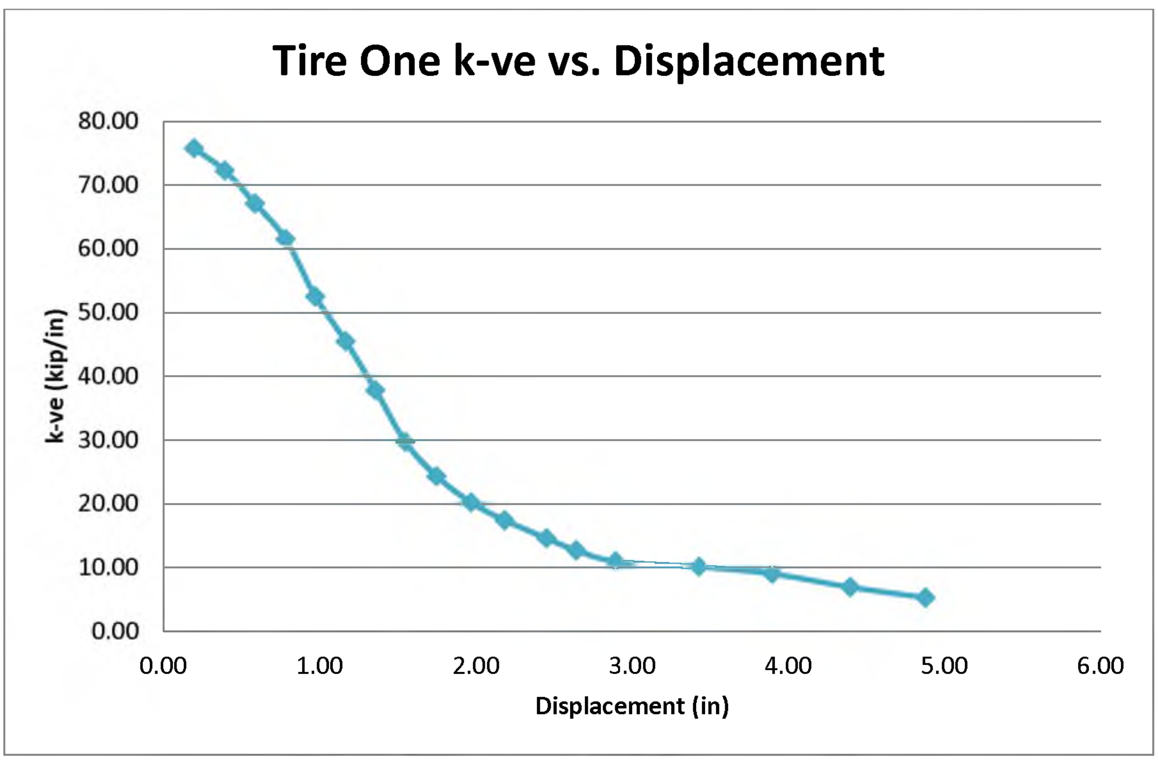


Figure 27 – Test One Negative Stiffness vs. Displacement

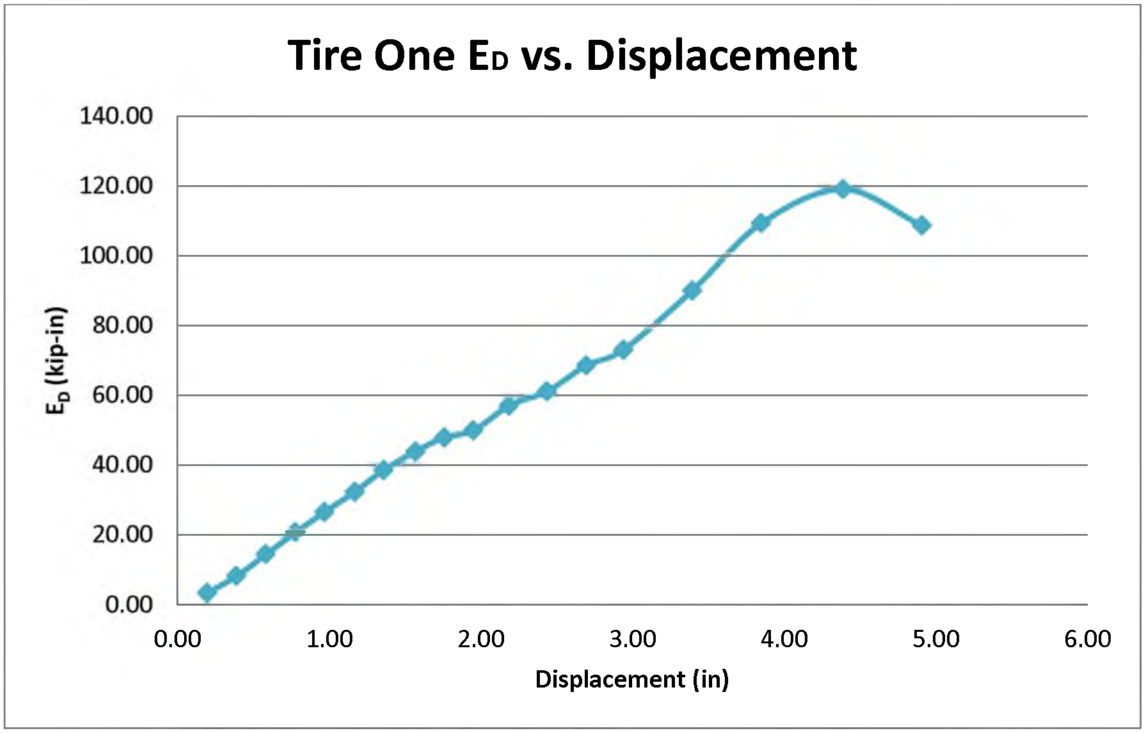


Figure 28 – Test One Damping Energy vs. Displacement

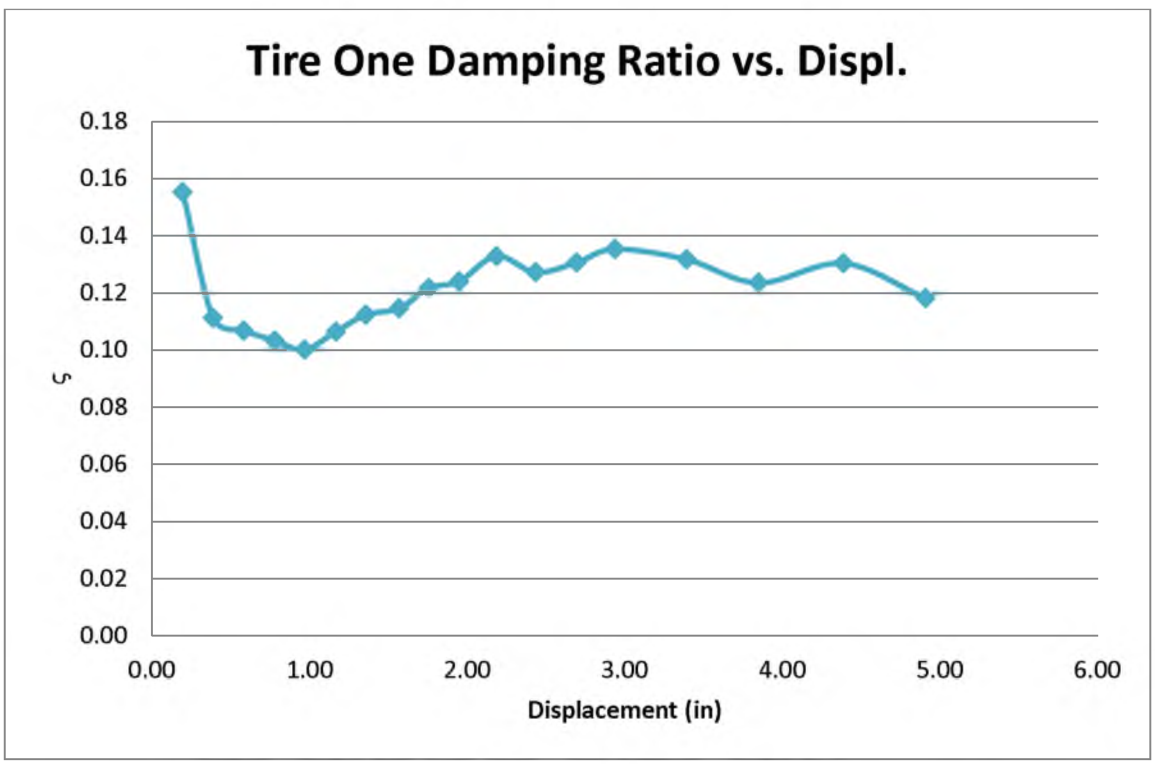


Figure 29 – Test One Damping Ratio vs. Displacement

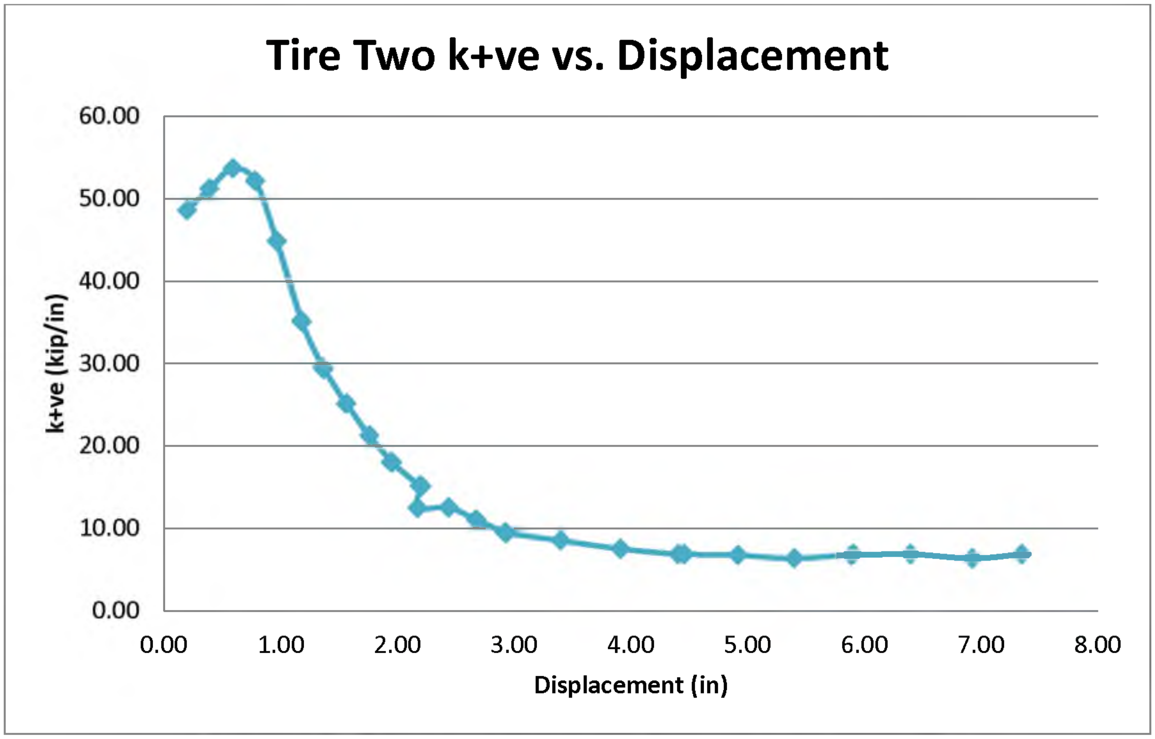


Figure 30 – Test Two Positive Stiffness vs. Displacement

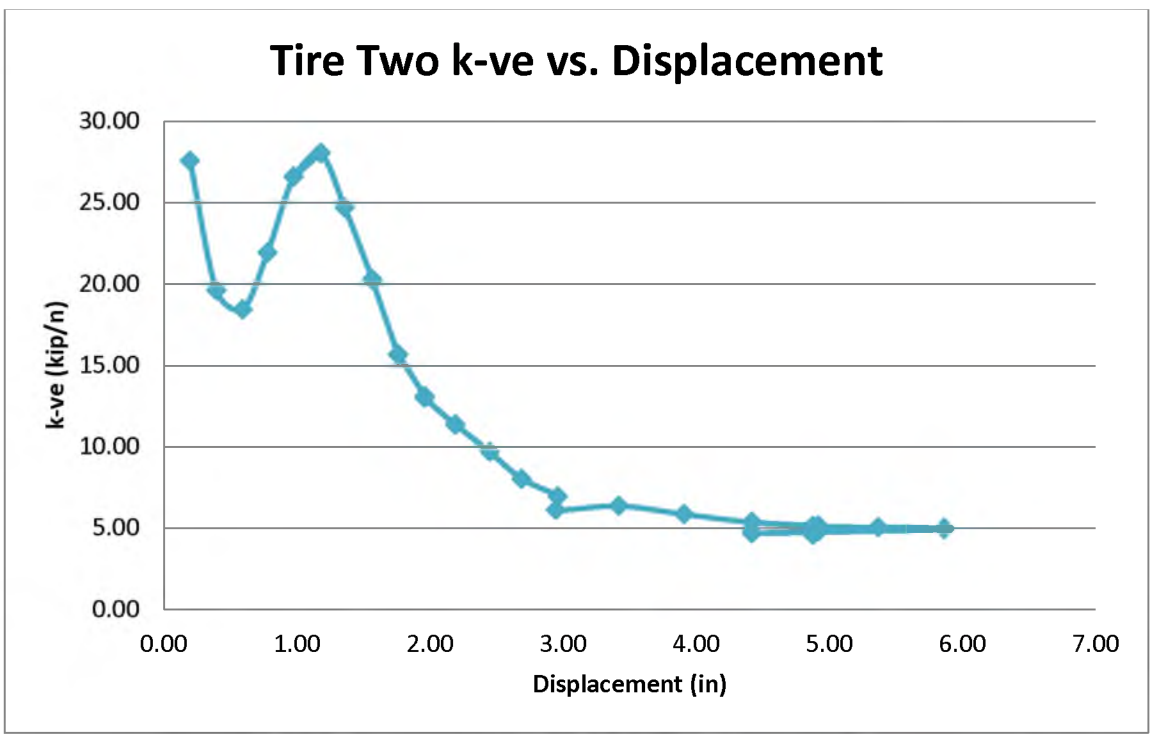


Figure 31 – Test Two Negative Stiffness vs. Displacement

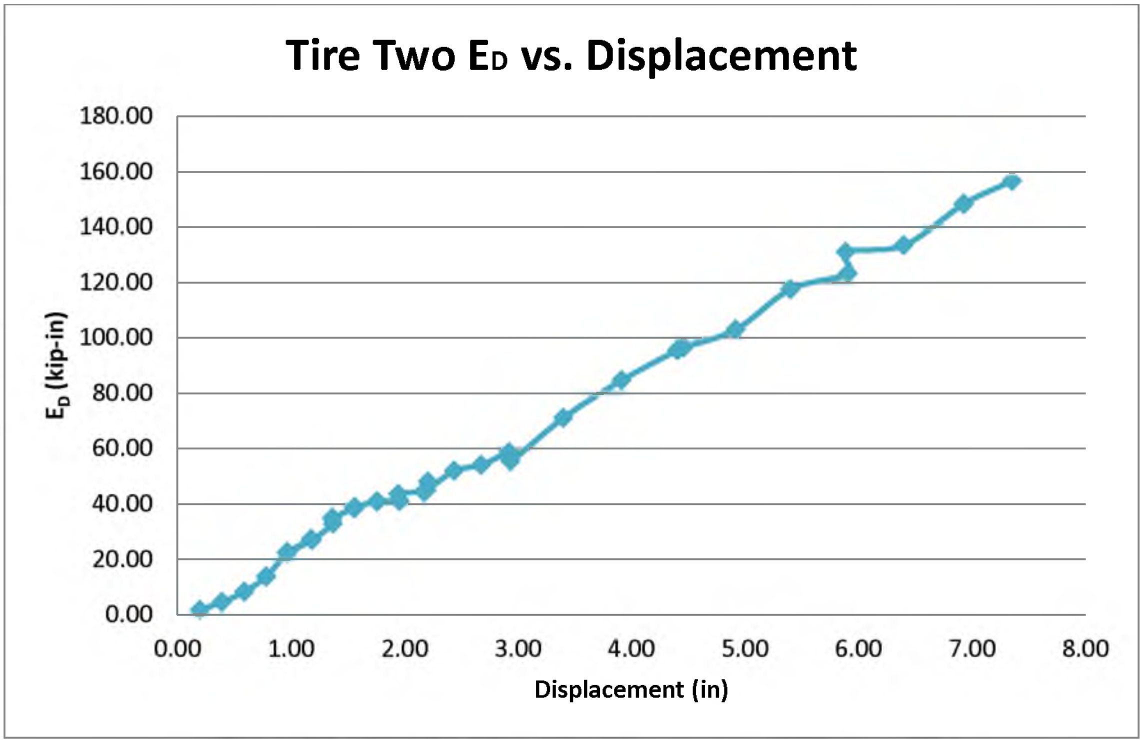


Figure 32 – Test Two Damping Energy vs. Displacement

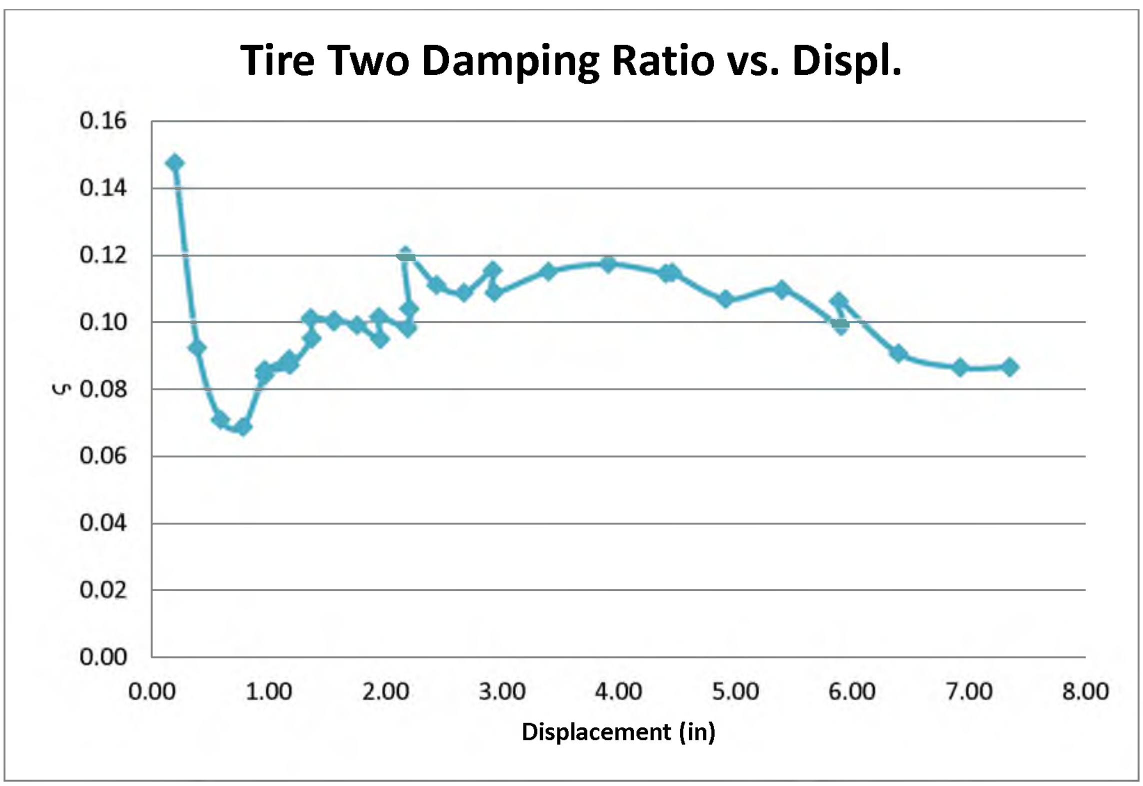


Figure 33 – Test Two Damping Ratio vs. Displacement

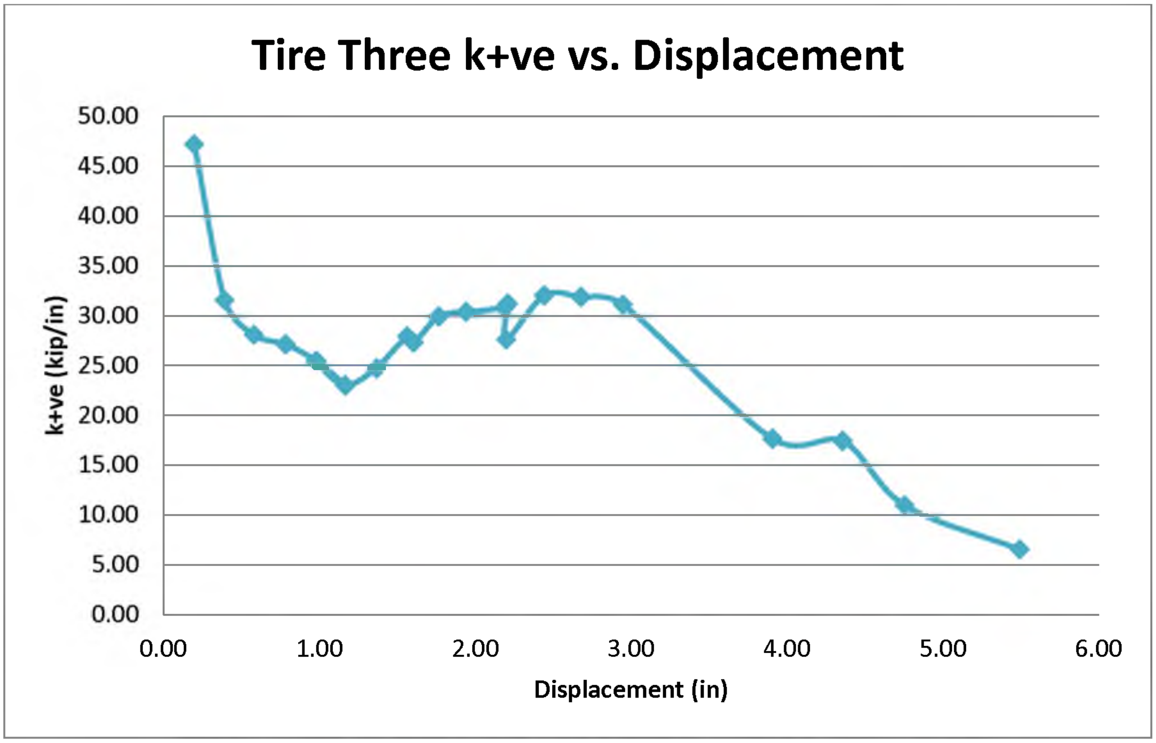


Figure 34 – Test Three Positive Stiffness vs. Displacement

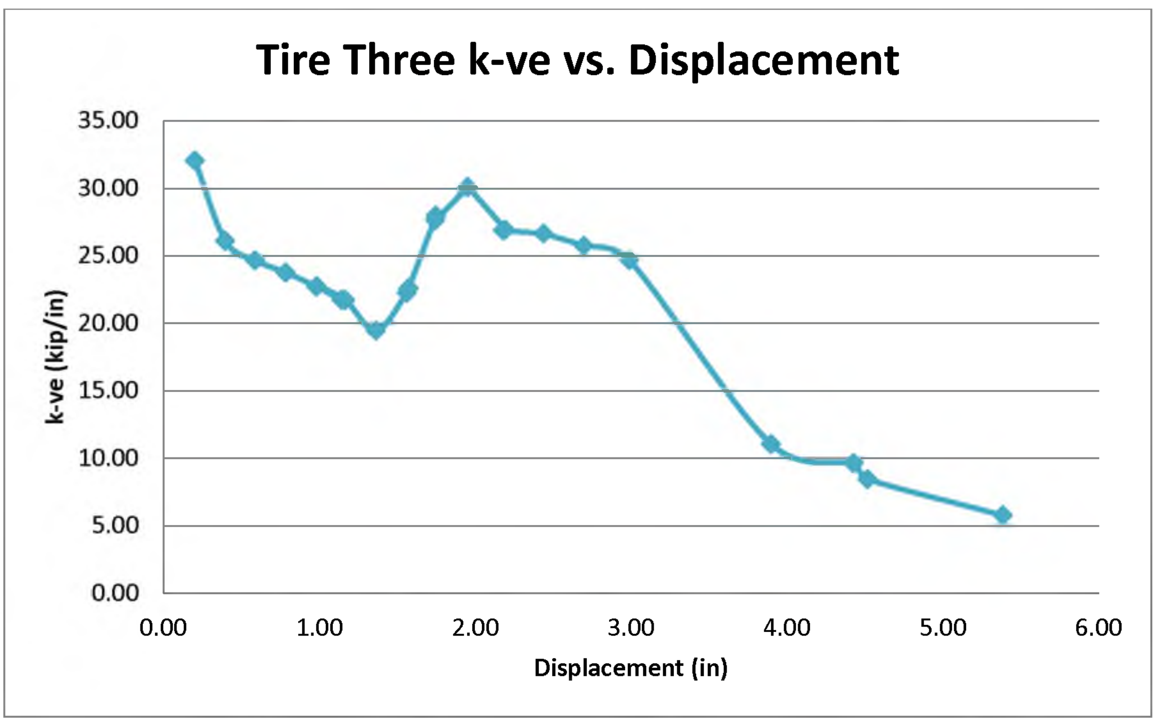


Figure 35 – Test Three Negative Stiffness vs. Displacement

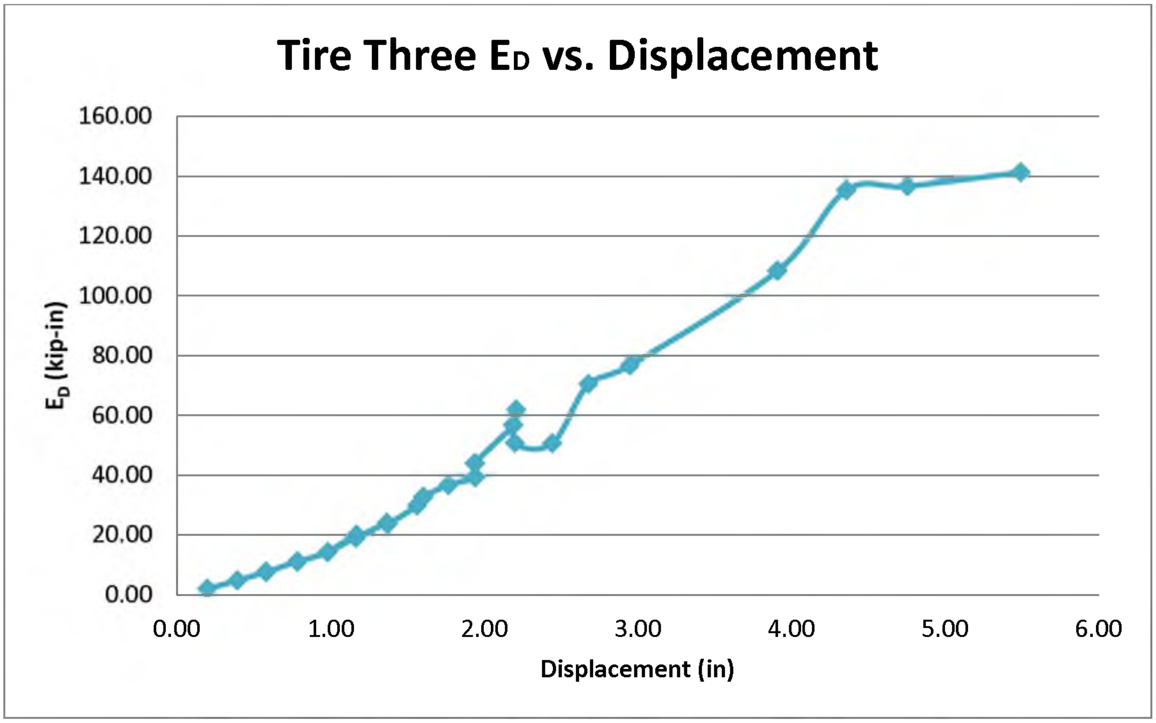


Figure 36 – Test Three Damping Energy vs. Displacement

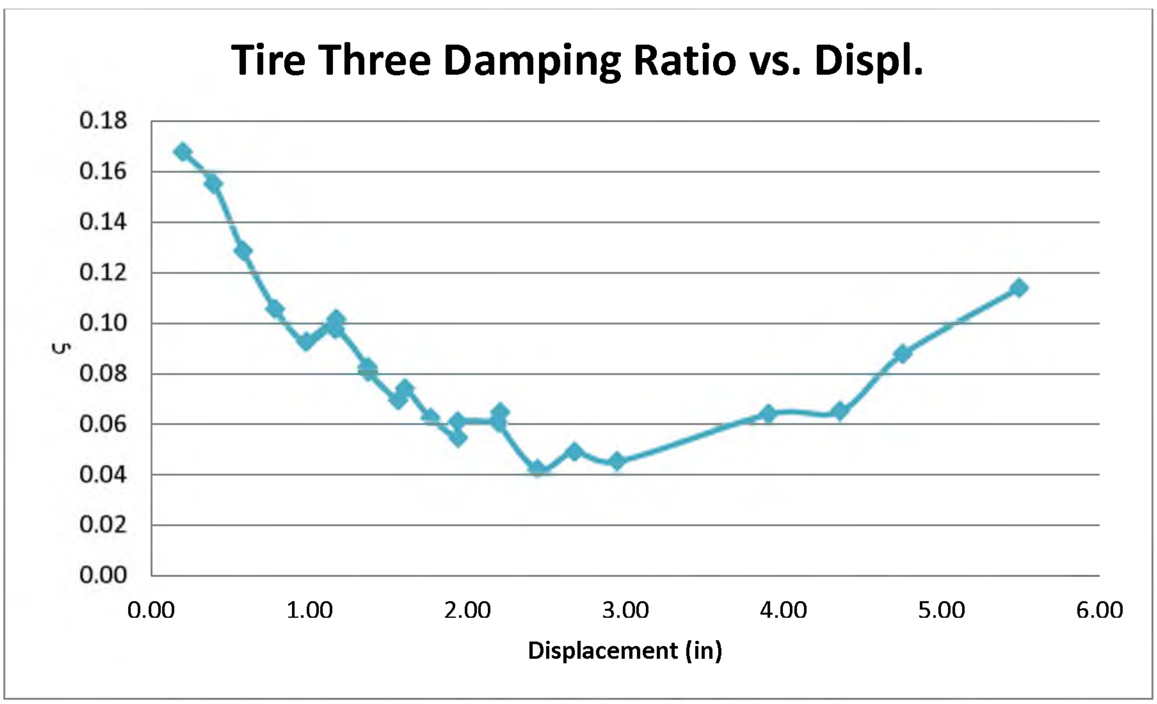


Figure 37 – Test Three Damping Ratio vs. Displacement

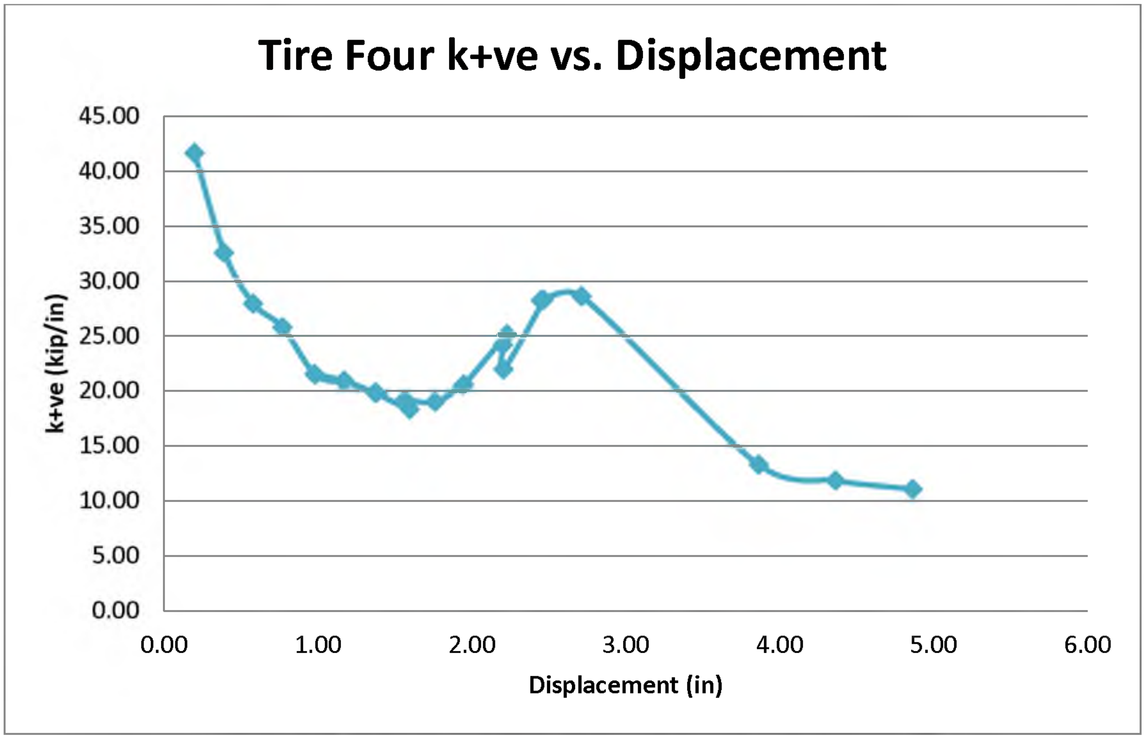


Figure 38 - Test Four Positive Stiffness vs. Displacement

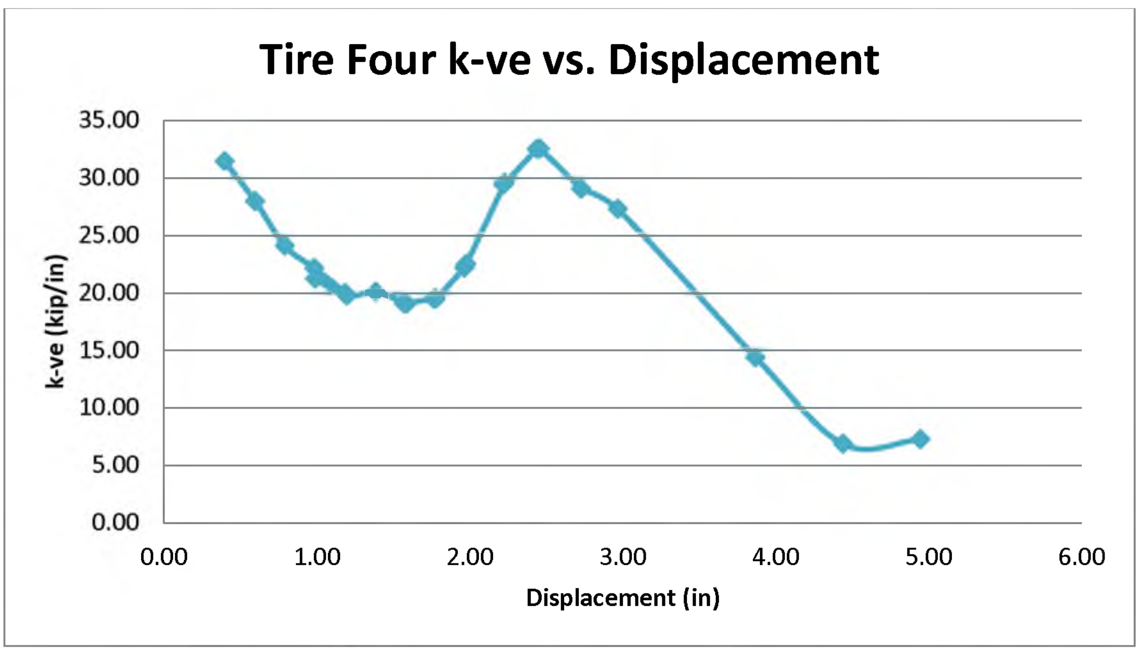


Figure 39 – Test Four Negative Stiffness vs. Displacement

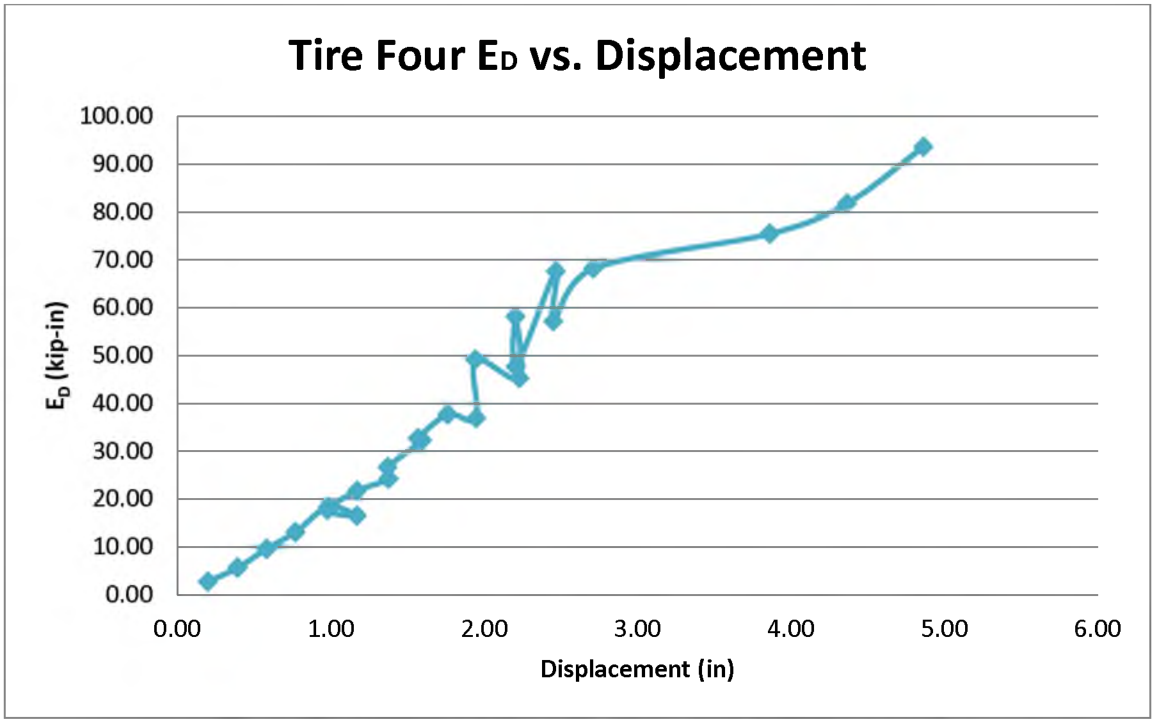


Figure 40 – Test Four Damping Energy vs. Displacement

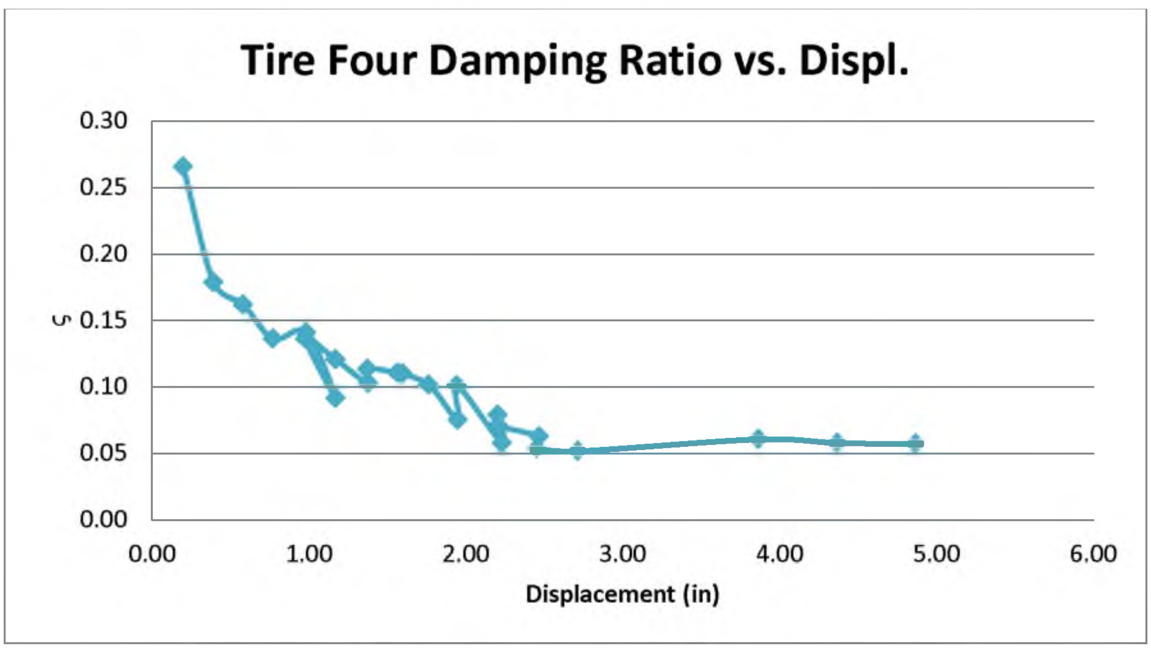


Figure 41 – Test Four Damping Ratio vs. Displacement

behaved, it was the only one that had no jumps in the data. Also witnessed in the hysteretic loop graphs, are loop ends that are not smooth. These jagged ends are attributed to breaking of the concrete. Failure of the system is the result of the damper doing its job and dissipating energy. A high level of pinching is seen in the hysteretic loops and thus, the loops are pinched in nature.

Four different tires were built and tested in the cross bracing frame. Test One and Test Two utilized reinforcement bars. The testing from tire one was the most consistent. The average damping ratio for this test was 0.12 and ranged from 0.10 to 0.14. Tire two was created with the same materials as tire one. Test Two had a damping ratio average of 0.10 and ranged from 0.07 to 0.12. Tests Three and Four were made with smooth rods instead of reinforcement bars. The results were more irregular than Test Two. The average damping ratio for this test was 0.08 and ranged from 0.04 to 0.15. The average damping ratio for this test was 0.10 and ranged from 0.05 to 0.18. It should be noted that the damping ratio never exceeded 0.14 in the second half of the test where the larger loadings were applied.

The above review of the data analysis shows that this damper works comparably to the more expensive dampers that are available. Additional research could be done, however, the damping ratios from the experimental data show that it would be successful.

It should be noted that damping values were not as reliable once out of the elastic damping range. This range ends where the yield point of the system occurred as a result of the failure of the system. If the damping had been reliable at the higher displacements that occurred outside of the elastic damping range, the damping ratios would have been much higher.

Table 7 summarizes the observations that were made from the maximum and residual forces for each test. The preliminary test which was discussed in the literature review is also included so that the influence of adding reinforcement to the damper can be seen. **Table 8** gives a summary of the stiffness in kips/in at different displacements. This table helps for a comparison to be made between all four tests.

Table 7 – Maximum Force and Residual Comparison

Test Number	Quadrant 1 (kips)	Quadrant 3 (kips)	Residual (kips)
Preliminary Test	42	33	13.5@2.5”
1	44	54	32@2”
2	44	34	35@2.6”
3	90	86	65@4”-6”
4	88	85	55@4”-6”

Table 8 – Stiffness (kips/in) at Specific Displacements Comparison

Test #	.5”	1”	1.5”	2”	3”	4”
1	68	45	25	16	10	9
2	52	45	26	18	9	8
3	29	25	26	30	31	17.6
4	30	21	19	20	-	12

The following conclusions can be made from the comparison in **Table 7**:

- Tests One and Two with reinforcement bar add only marginally to the peak force which is seen in the preliminary test.
- The reinforcement bar increases the residual capacity of the damper by approximately 2.5 times.
- The reinforcement bar increases the deformation capacity by 2 times – at residual strengths.
- Yielding bolts in Tests Three and Four supply greater energy adsorption than other materials which results in wider loops.

The following conclusions can be made from the comparison in **Table 8**:

- The initial magnitude of the tire damper stiffness with the rods is significantly less than the initial magnitude of stiffness for tire damper with the steel hoops.
- Stiffness of the tire damper is more stable at large deflections.
- Hysteretic pinching is more prominent in the tests with rods than it is in the tests with the reinforcement bar due to the direct yielding of the rods.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Thesis Summary

The damper studied in this thesis was created to provide an unusual and innovative sustainable approach to the structural damping of buildings. From testing it appears that this would be a suitable and unique approach that should be cost effective because of the materials involved.

It was the hope at the start of this project that the tire damper would provide results that are similar to modern day dampers at a fraction of the cost. Typical damping ratios are 0.05. The damping ratios found in this research show damping ratios between 0.04 and 0.18. This compares favorably to typical damping ratios.

This tire damper may be able to be improved with additional research, but has shown great potential based on analysis of the data. It has proven to be a viable device which can be used in many different scenarios, from low-rise buildings to industrial buildings. It may not provide the same high-quality level as typical structural dampers. The results of the data show that future research is warranted and may increase the quality of the tire damper design which is presented in this thesis.

6.2 Conclusions

This tire damper does provide a sufficient level of structural damping that can be used in low-rise buildings, but more importantly it provides the frame with yielding characteristics. This yielding is a result of the stiffness of the bracing in combination with the ductility of the damper. This will in turn lengthen the fundamental period of the system in comparison to typical braced frames, decreasing the base shear and increasing the period of the structure. This will help the frame to not fracture or be too rigid. Additionally, this tire damper allows the frame to be subjected to large displacements, but still withstand large forces. The damper has also demonstrated significant damping characteristics.

In conclusion, the data research analysis has shown that the tire damper is a viable system. Of the tests that were done, it appears that the reinforcement bar tests provided more consistent damping ratio results which ranged from 0.07 to 0.14. The Third and Fourth tests (smooth rods) had damping ratios that varied greatly during testing compared to the first two tests, but had much greater residual capacity.

6.3 Recommendations

Through the different tests, it was noted that the tire rubber tended to rupture at the pin connection. This is because a hole was cut in the tire for I bolt. It is possible that the tire could be reinforced around the I-bolt hole to improve the strength of the damper.

Another recommendation to improve testing in the future is to be careful with the loop placement of the reinforcement bar. This gives the test greater control. The great difference between Tests One and Two show that the placement of the reinforcement bar loops is critical.

6.4 Recommendations for Future Research

The third and fourth tests which utilized rods as the dampers reinforcement had a higher ultimate loading capacity. It is therefore recommended the rods in those tests be combined with reinforcement bar, or a substitute. It is possible that the beading from a scrap tire can be used as the reinforcement bar.

Another option to increase the strength of the damper would be for the tire to be wrapped in fiber glass rather than duct tape. Fiber glass has a stronger tensile strength than the duct tape. This design improvement will give the damper a higher-loading capacity than it had in the previous tests.

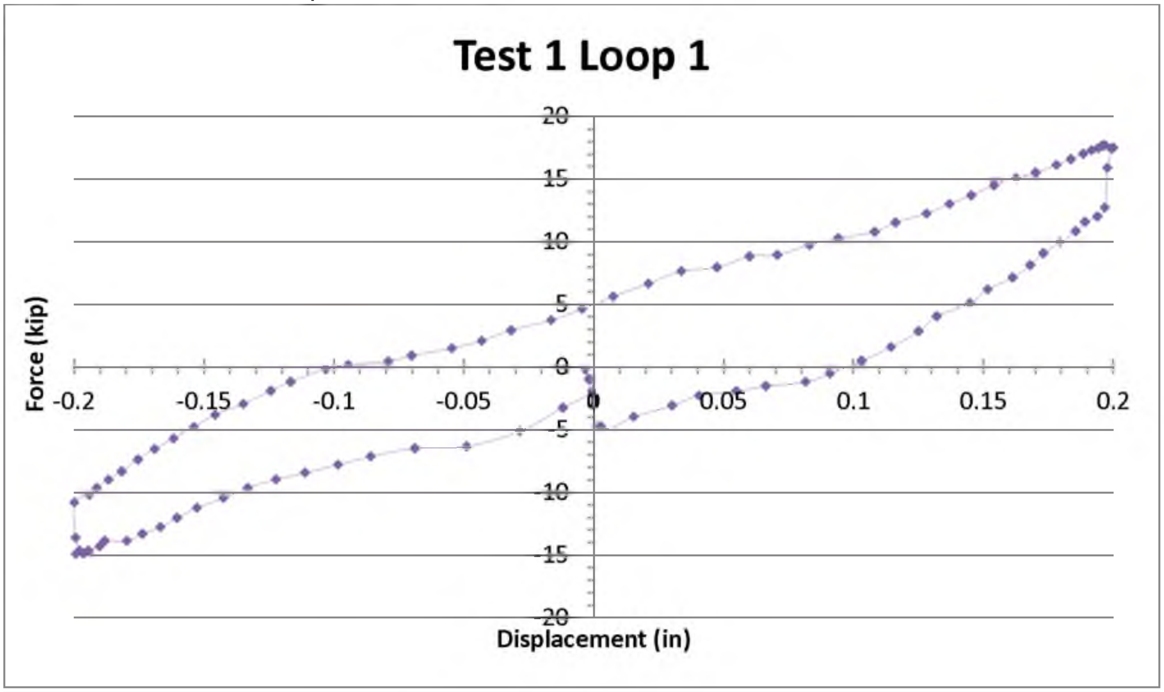
ANSYS software can be used to predict the loading capacity before the sample is built. This way, the design can be optimized. Running physical testing on only the optimized designs will save a great deal of time.

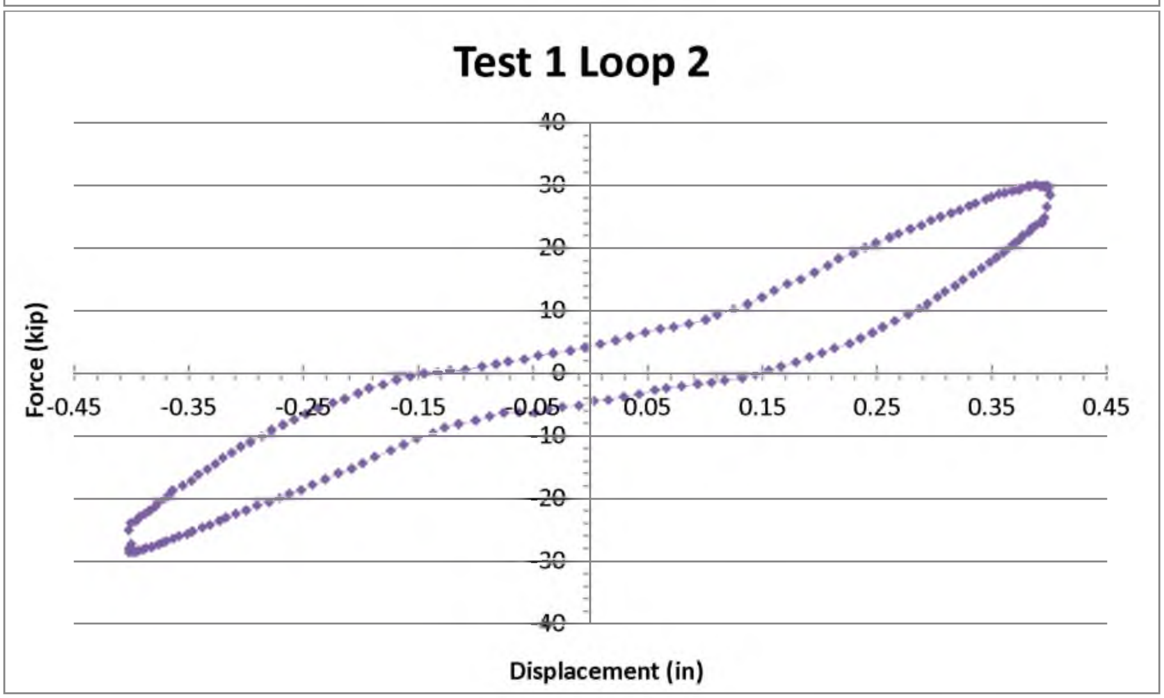
The tire damper could be used in areas where more than just earthquakes are a threat to help make structures more disaster resistant. Often, tsunamis come in response to earthquakes. In areas that are prone to have both of these natural disasters occur in succession, this damper could resist high-wind loading and the impact of tsunamis in addition to providing earthquake resistance. It is suggested that future research on this damper could be combined with additional disaster resistant designs to further the impact of the damper in cases where more than one natural disaster threat exists.

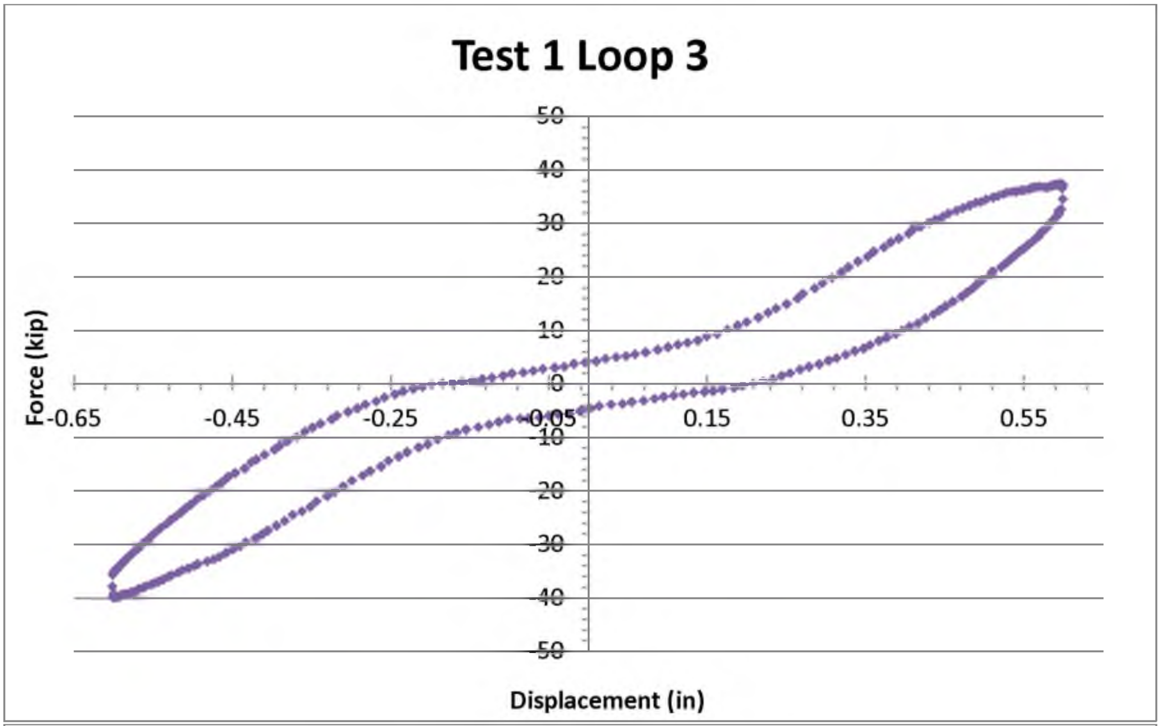
APPENDIX A

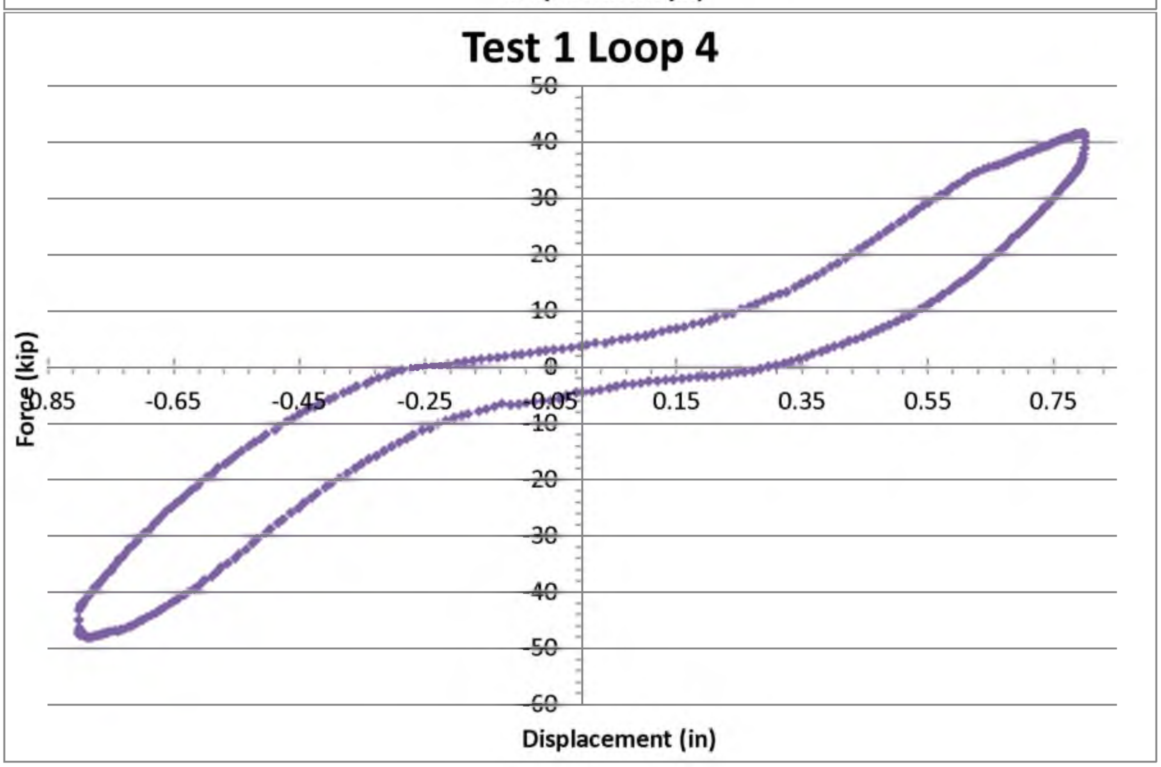
INDIVIDUAL LOOPS

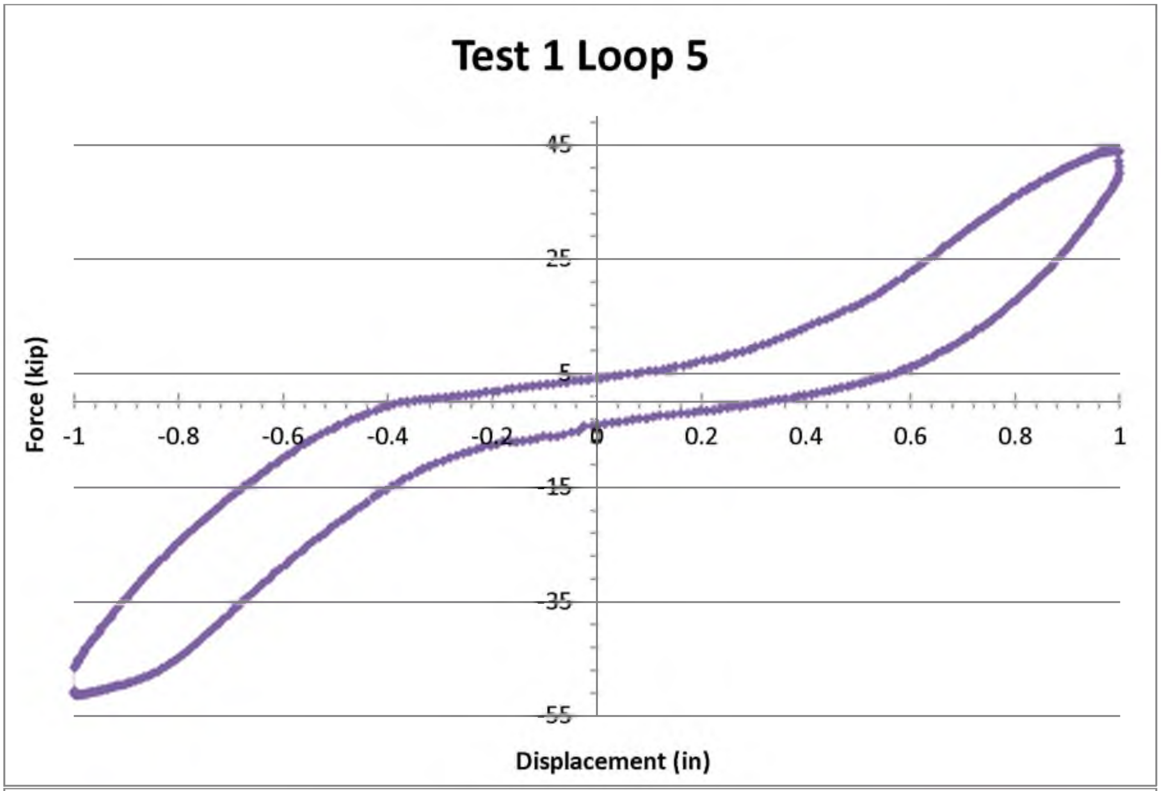
Test One Individual Loops – 18 Total

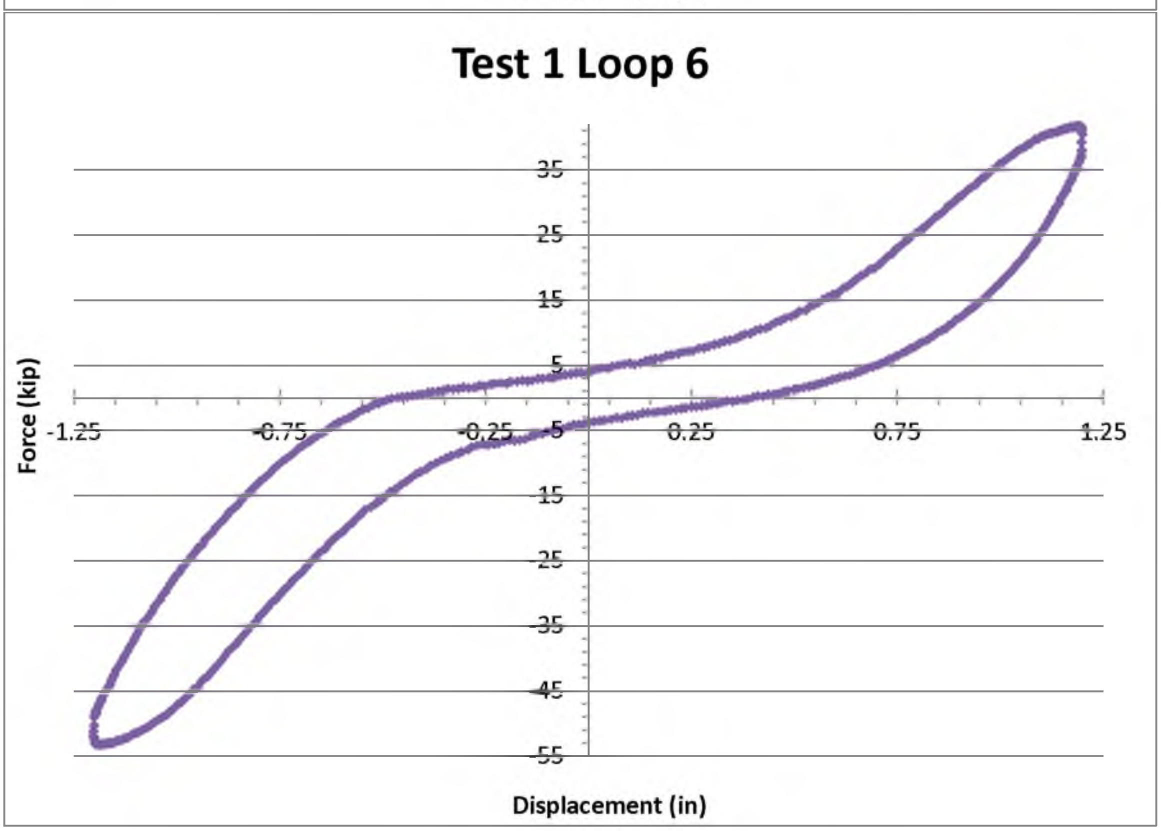


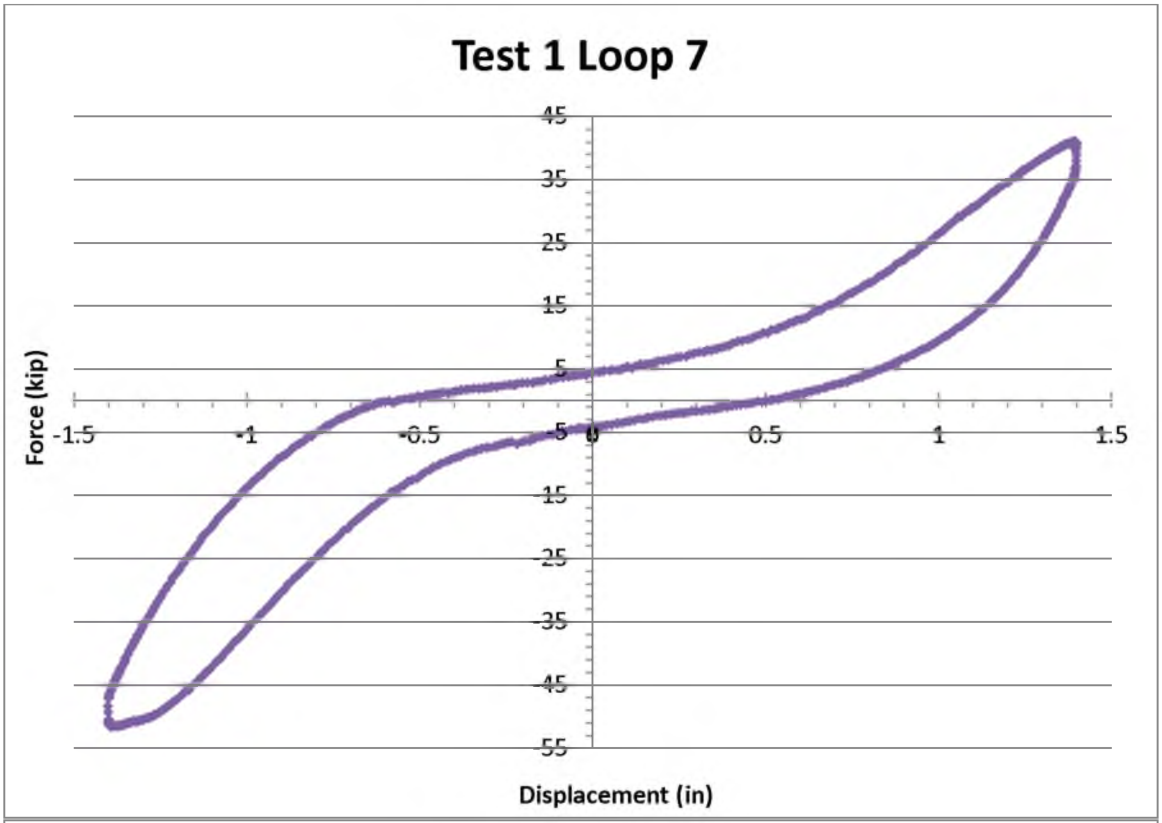


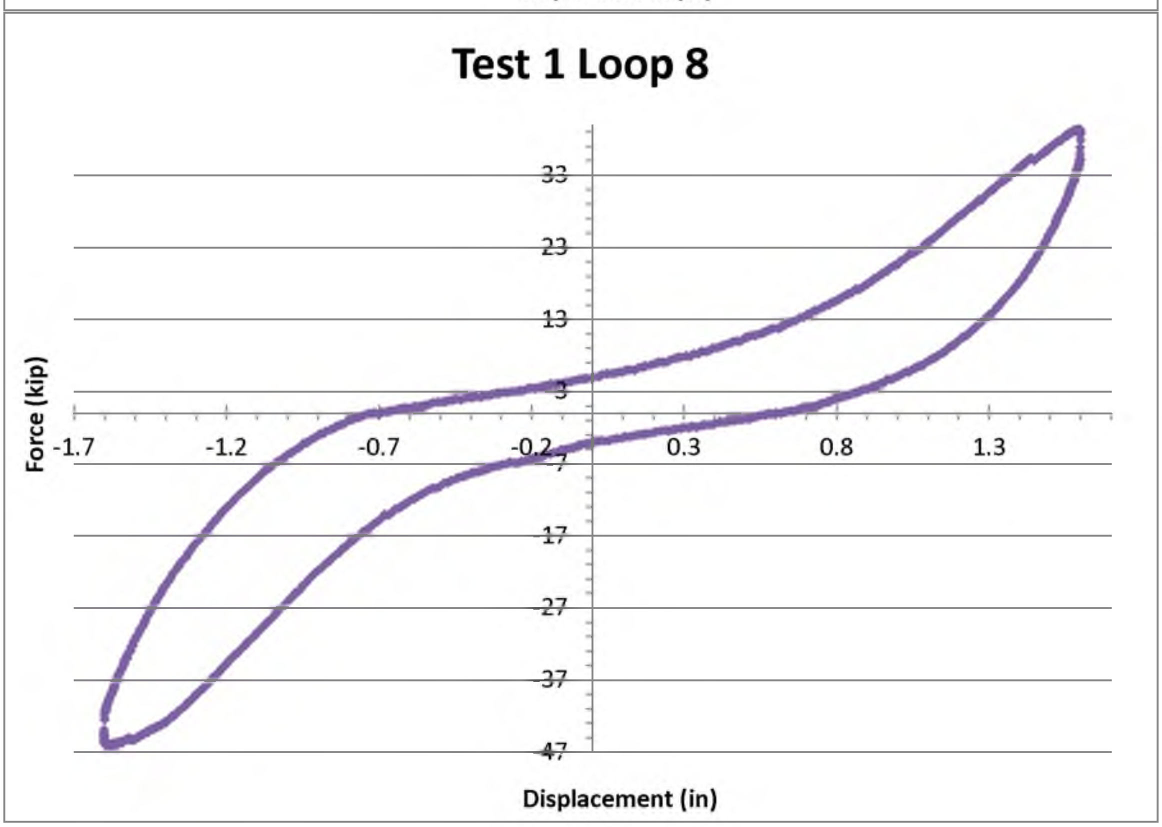

Test 1 Loop 3
50
40
30
20
10
0
-10
-20
-30
-40
-50
Force (kip)
-0.65
-0.45
-0.25
-0.05
0.15
0.35
0.55
Displacement (in)

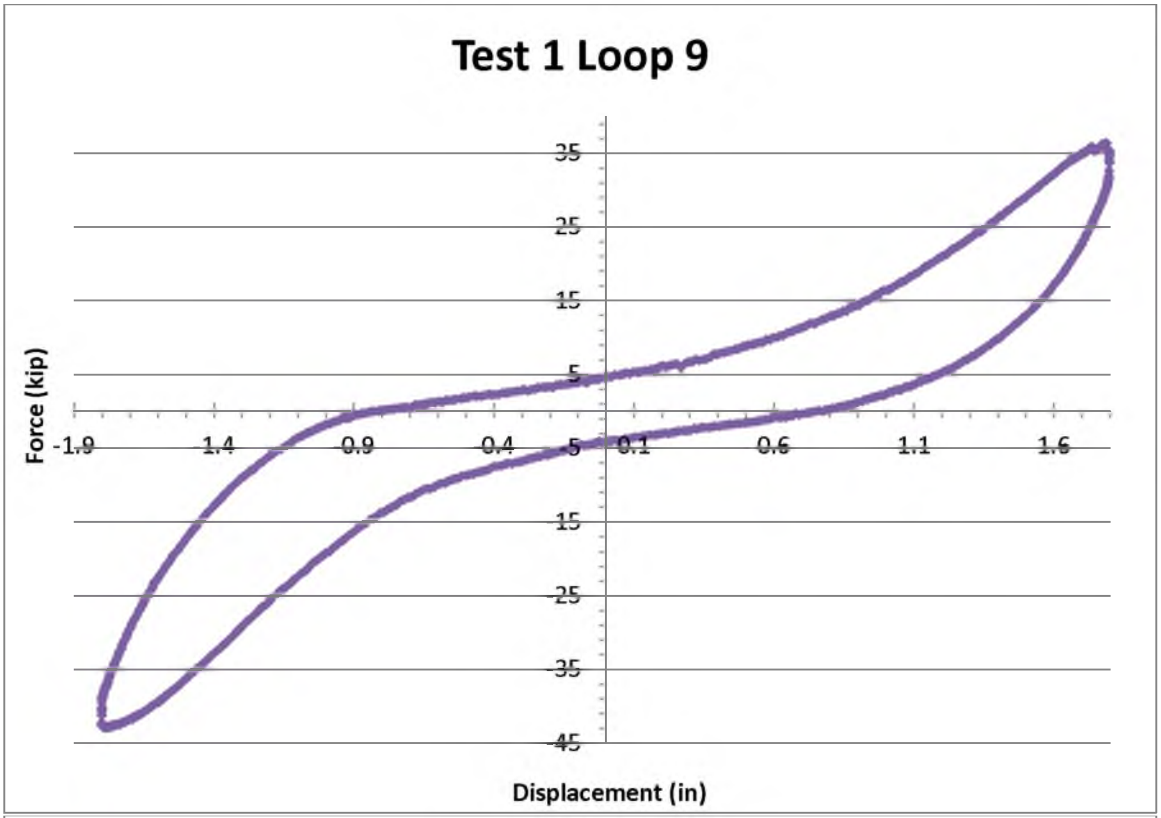

Test 1 Loop 4
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
Force (kip)
-0.85
-0.65
-0.45
-0.25
-0.05
0.15
0.35
0.55
0.75
Displacement (in)

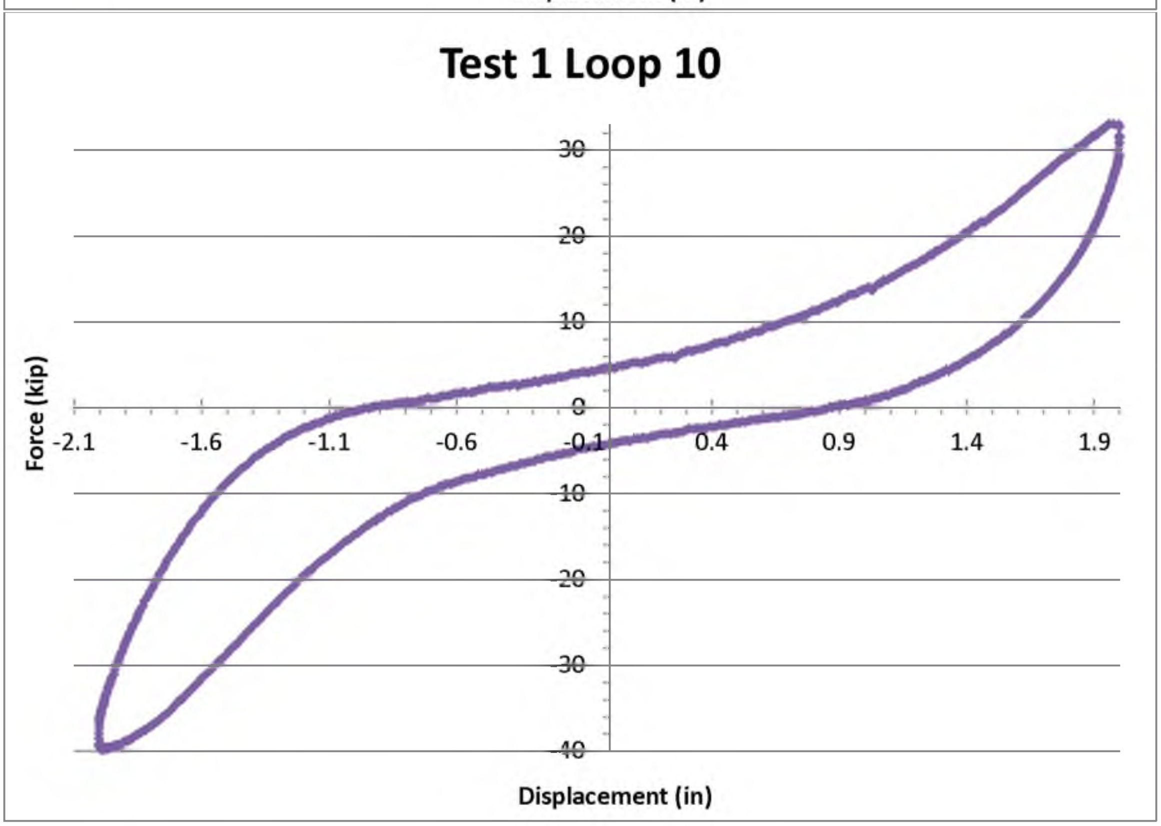

Test 1 Loop 5
45
25
5
-15
-35
-55
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Force (kip)
Displacement (in)

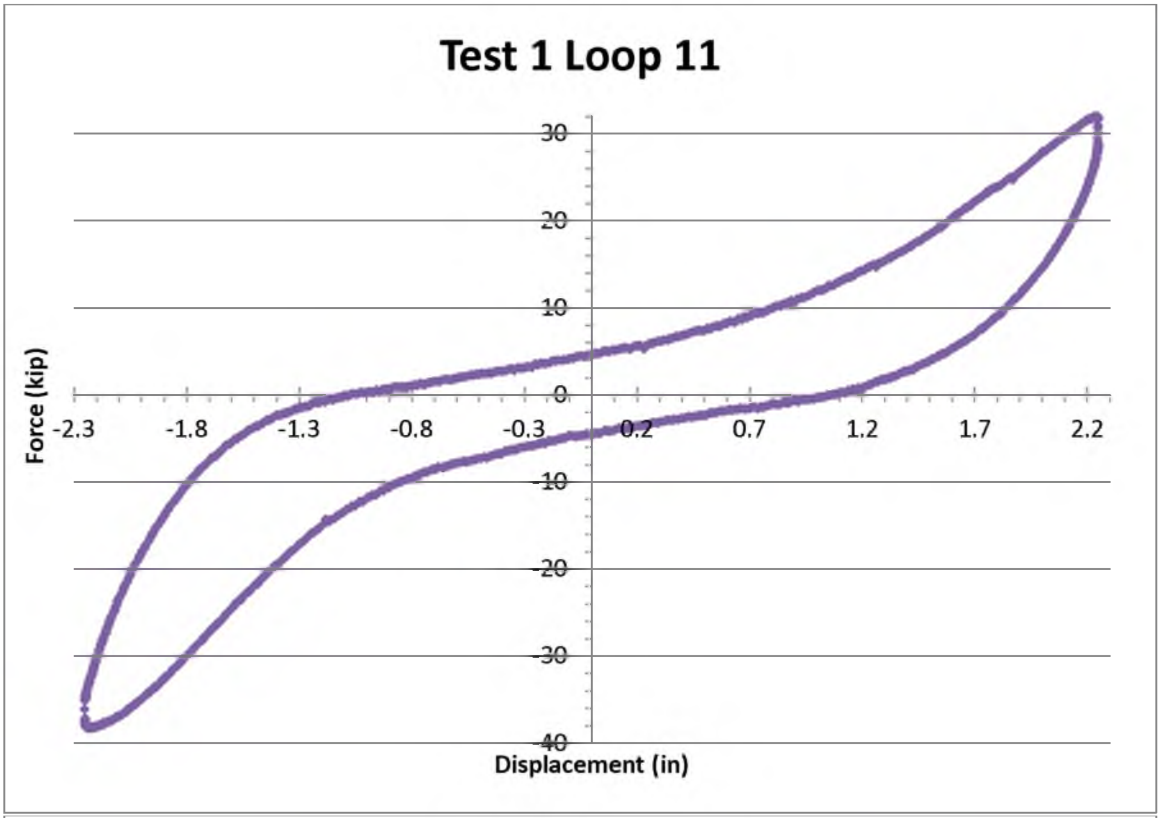

Test 1 Loop 6
35
25
15
5
-5
-15
-25
-35
-45
-55
-1.25
-0.75
-0.25
0.25
0.75
1.25
Force (kip)
Displacement (in)

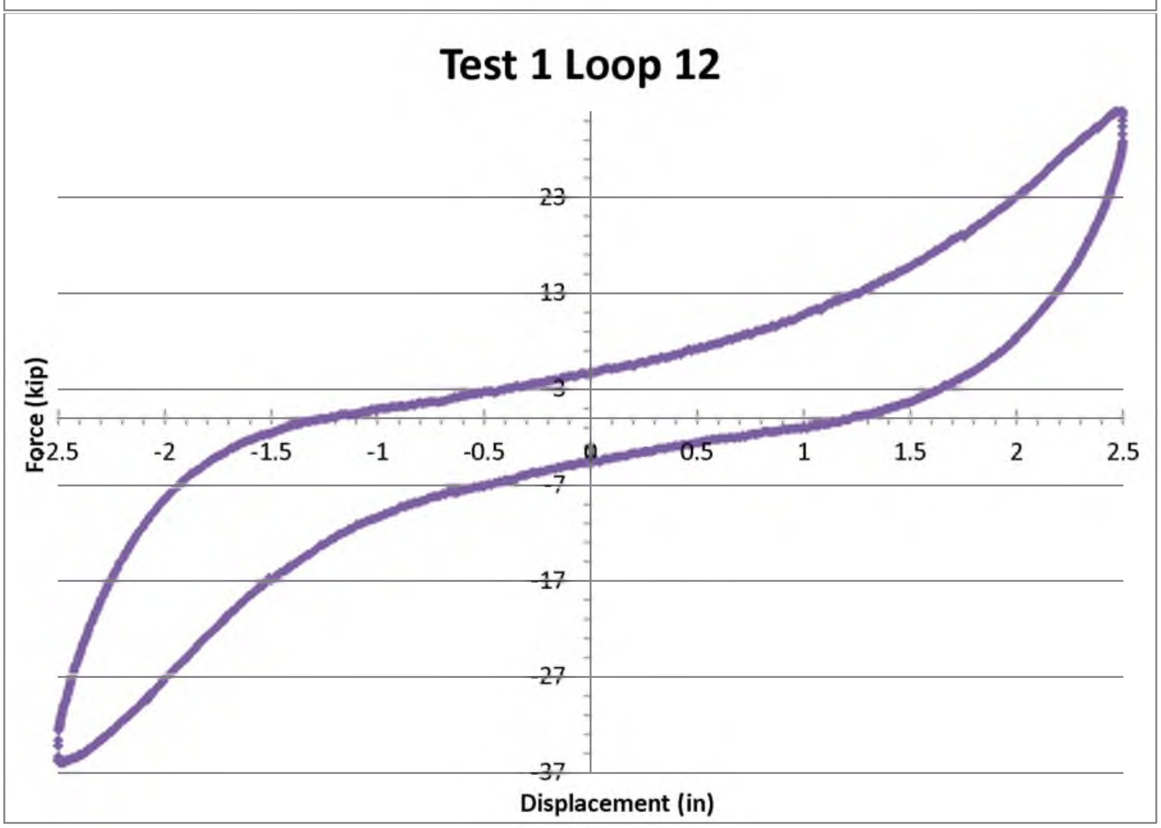

Test 1 Loop 7
Force (kip)
45
35
25
15
5
-5
-15
-25
-35
-45
-55
-1.5
-1
-0.5
0
0.5
1
1.5
Displacement (in)

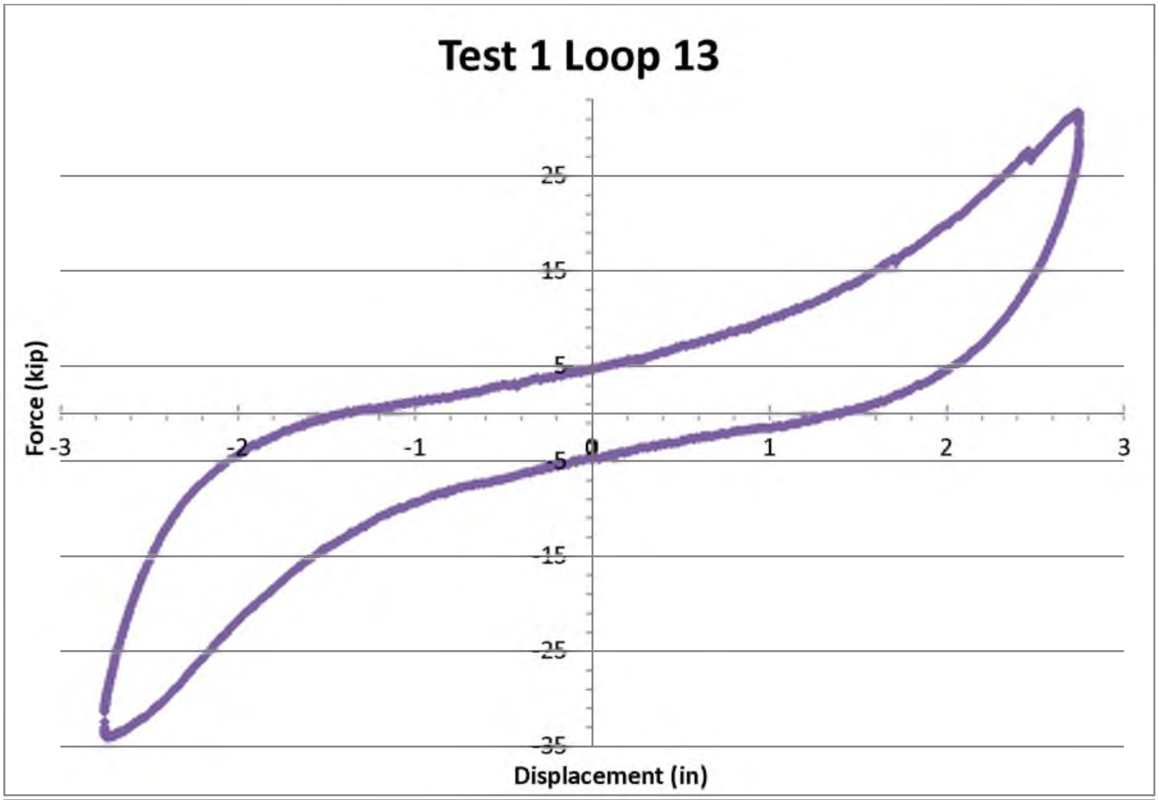

Test 1 Loop 8
Force (kip)
33
23
13
3
-7
-17
-27
-37
-47
-1.7
-1.2
-0.7
-0.2
0.3
0.8
1.3
Displacement (in)

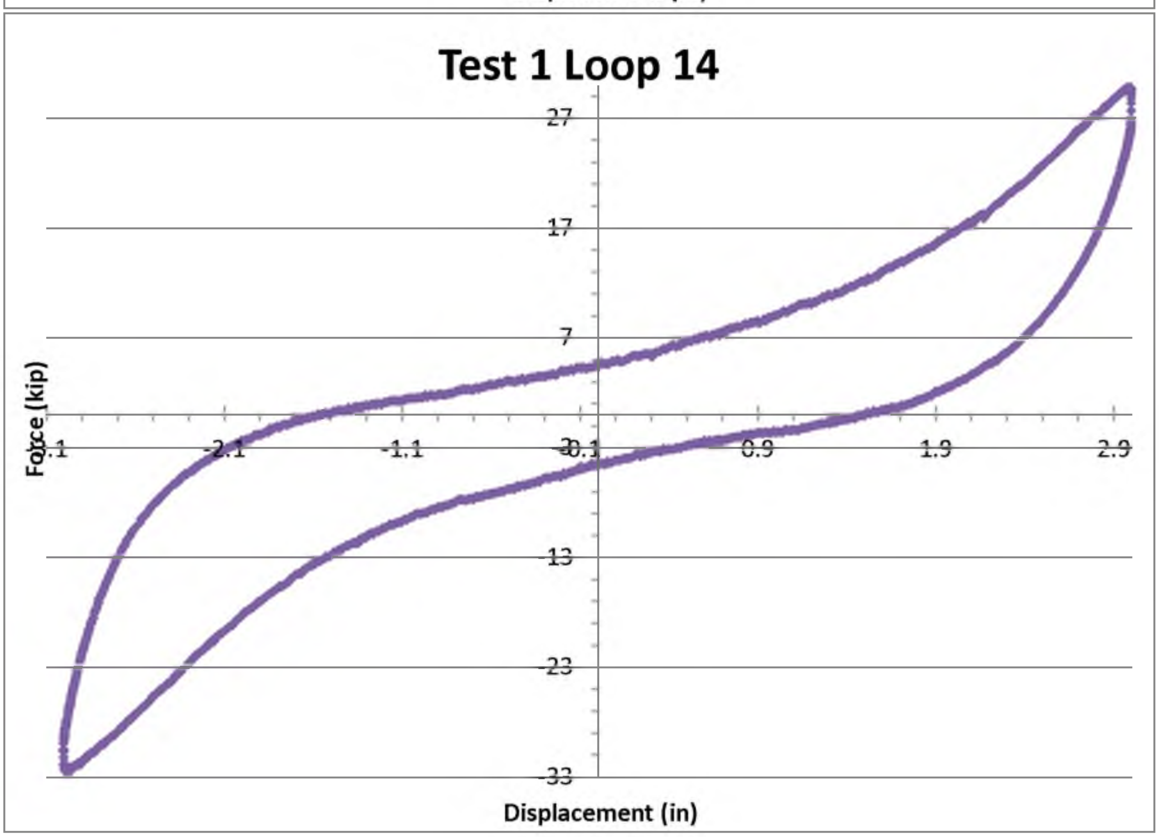

Test 1 Loop 9
Force (kip)
Displacement (in)
35
25
15
5
-5
-15
-25
-35
-45
-1.9
-1.4
-0.9
-0.4
0.1
0.6
1.1
1.6

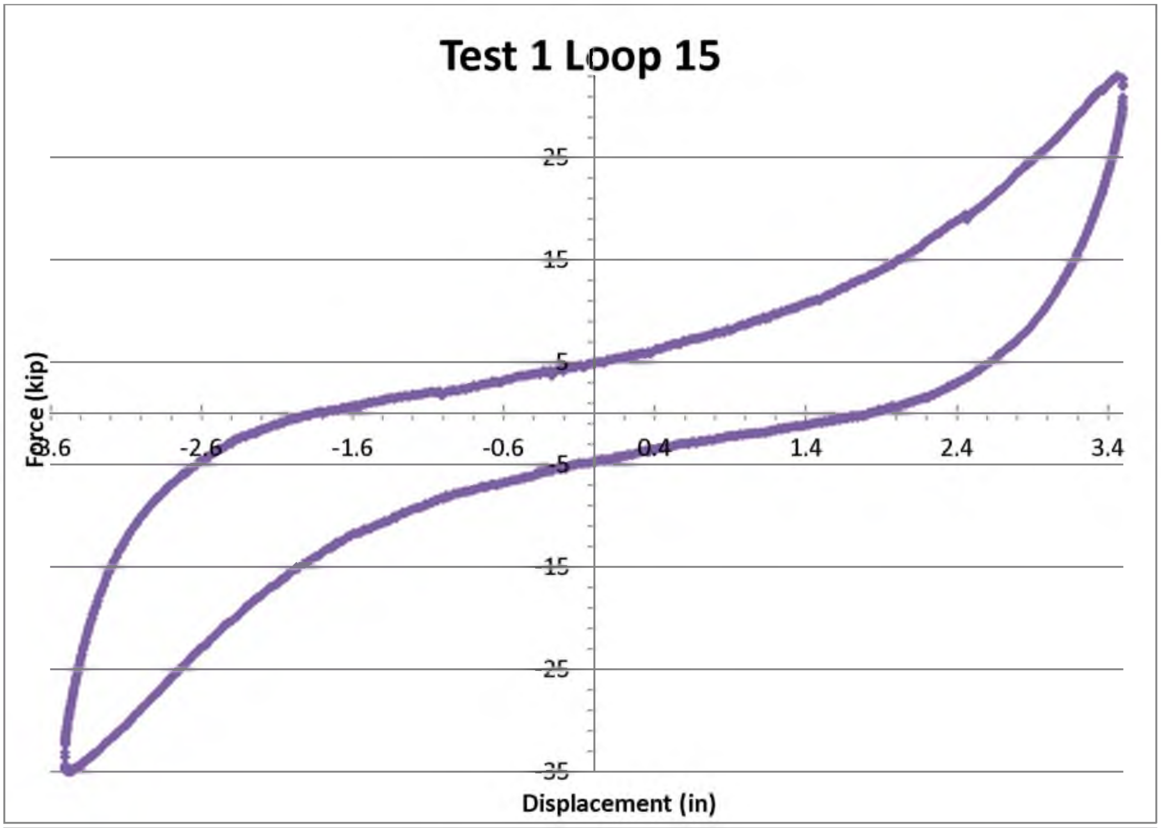

Test 1 Loop 10
Force (kip)
Displacement (in)
30
20
10
0
-10
-20
-30
-40
-2.1
-1.6
-1.1
-0.6
-0.1
0.4
0.9
1.4
1.9

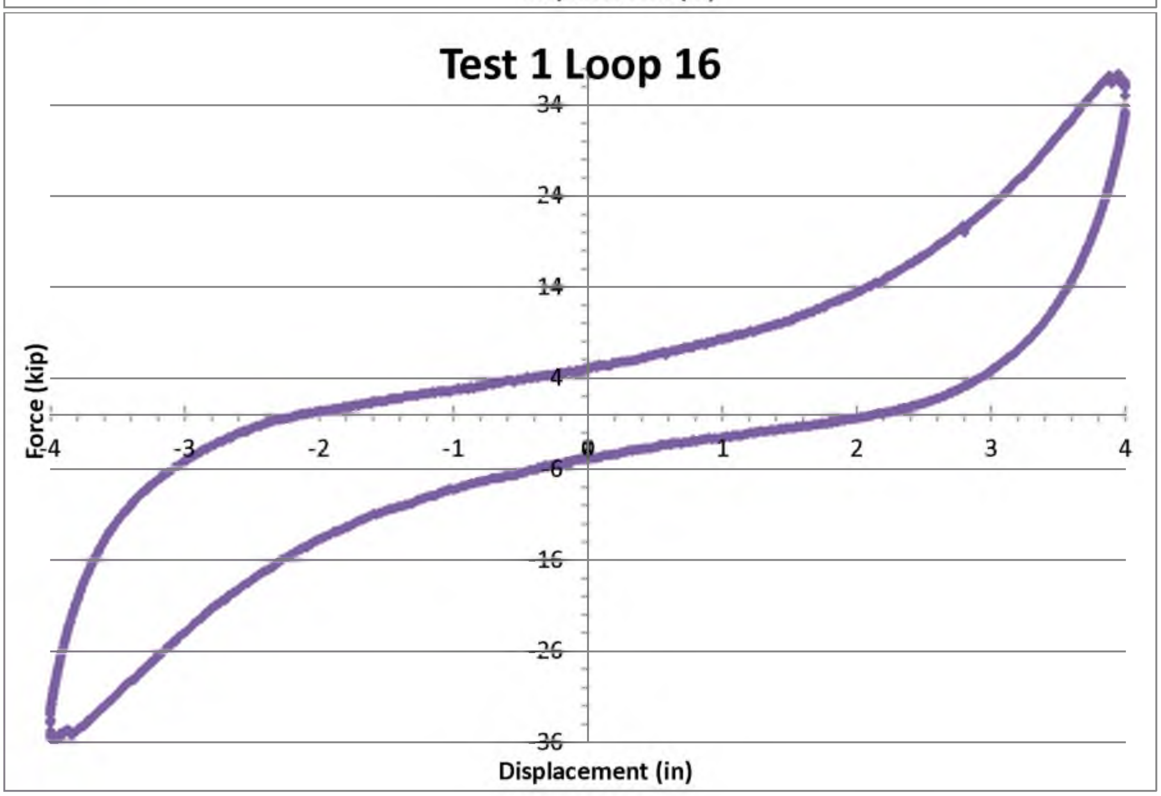

Test 1 Loop 11
Force (kip)
Displacement (in)
30
20
10
0
-10
-20
-30
-40
-2.3
-1.8
-1.3
-0.8
-0.3
0.2
0.7
1.2
1.7
2.2

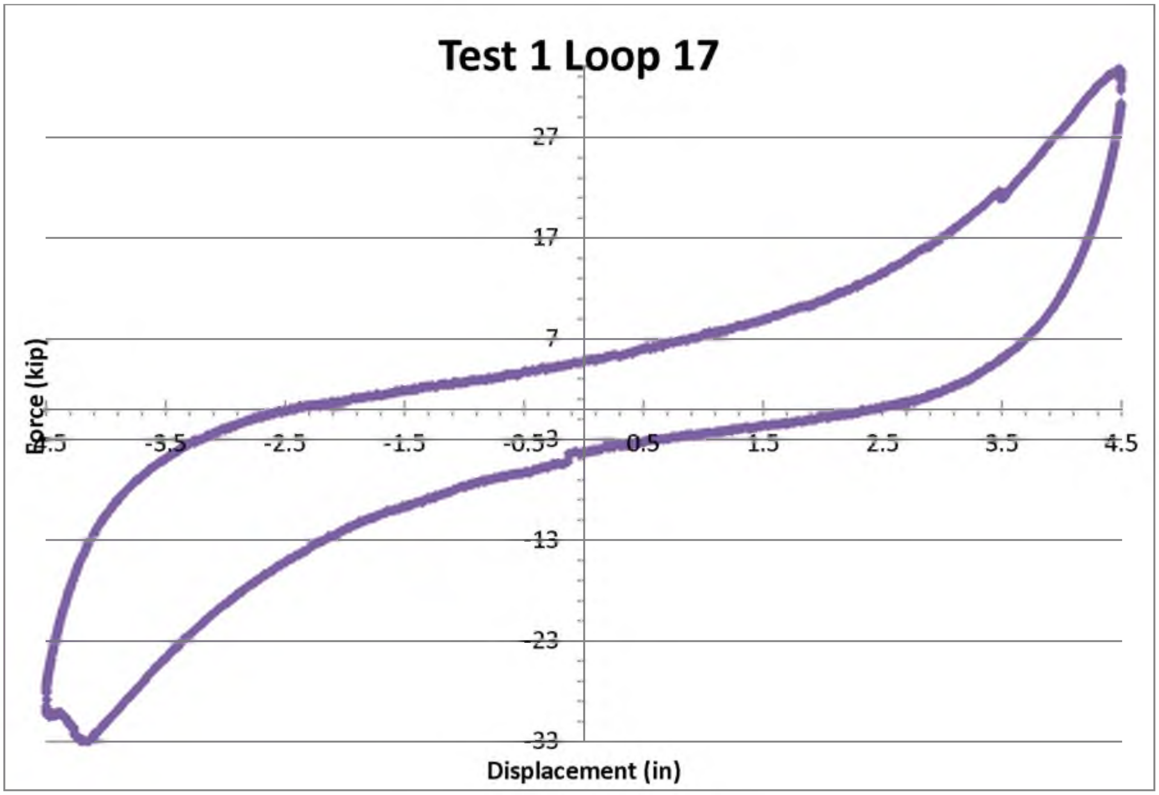

Test 1 Loop 12
Force (kip)
Displacement (in)
23
13
3
-7
-17
-27
-37
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5

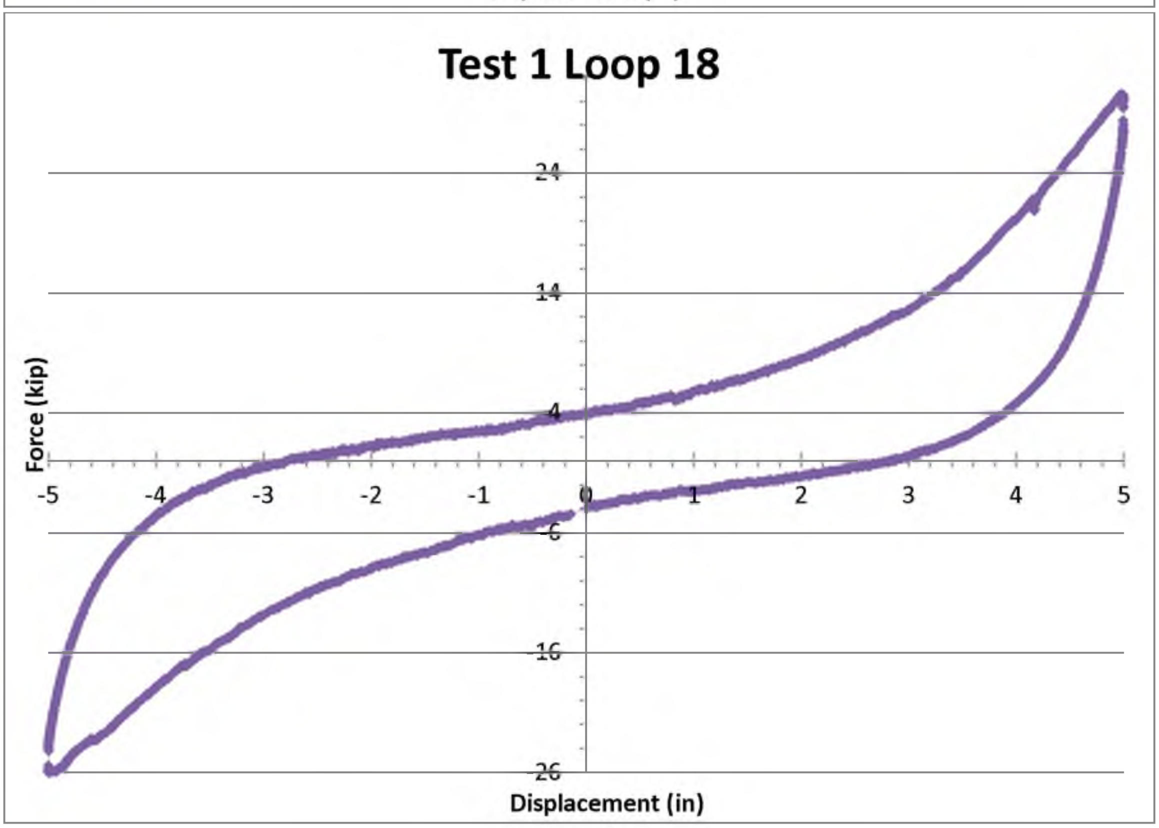

Test 1 Loop 13
Force (kip)
Displacement (in)
25
15
5
-5
-15
-25
-35
-3
-2
-1
0
1
2
3


Test 1 Loop 14
Force (kip)
Displacement (in)
27
17
7
-13
-23
-33
-2.1
-1.1
-0.1
0.9
1.9
2.9

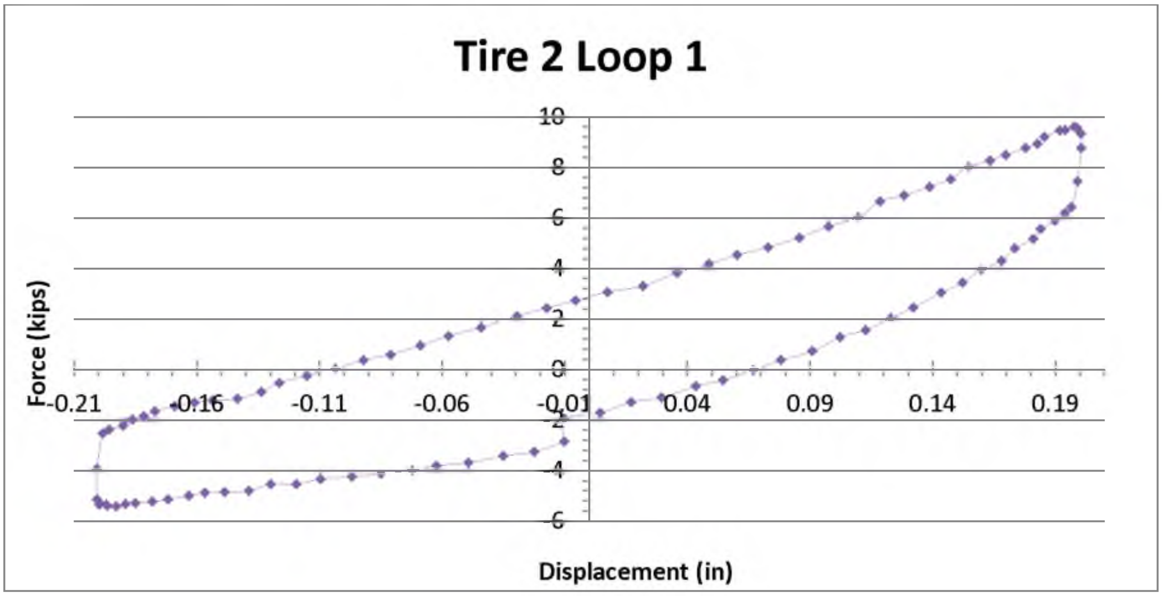

Test 1 Loop 15
25
15
5
-5
-15
-25
-35
-3.6
-2.6
-1.6
-0.6
0.4
1.4
2.4
3.4
Force (kip)
Displacement (in)

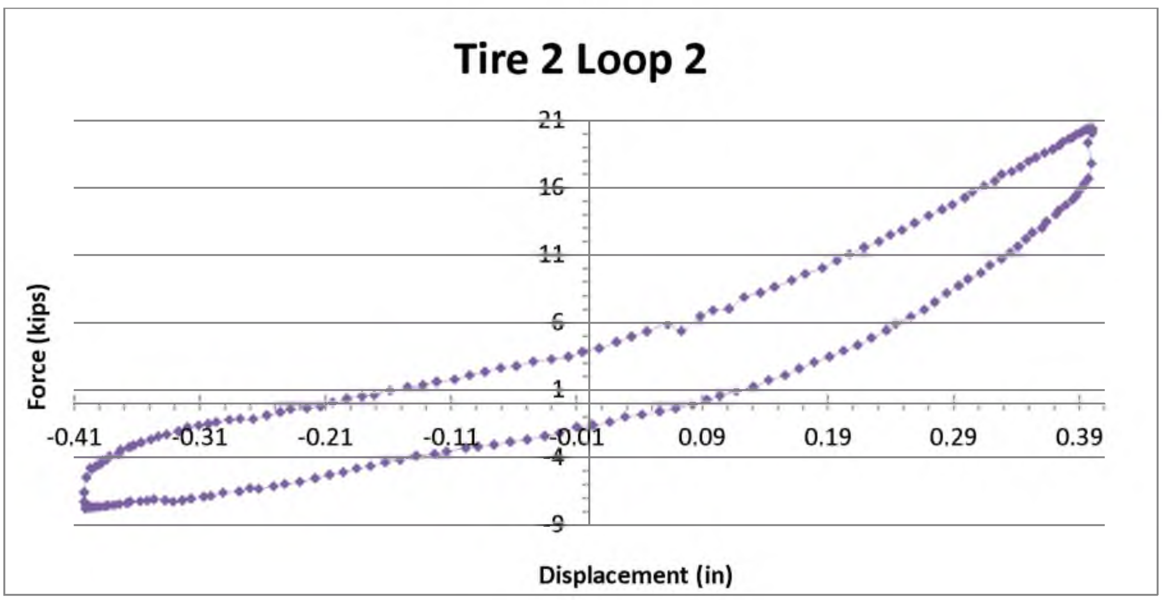

Test 1 Loop 16
34
24
14
4
-6
-16
-26
-36
-4
-3
-2
-1
0
1
2
3
4
Force (kip)
Displacement (in)

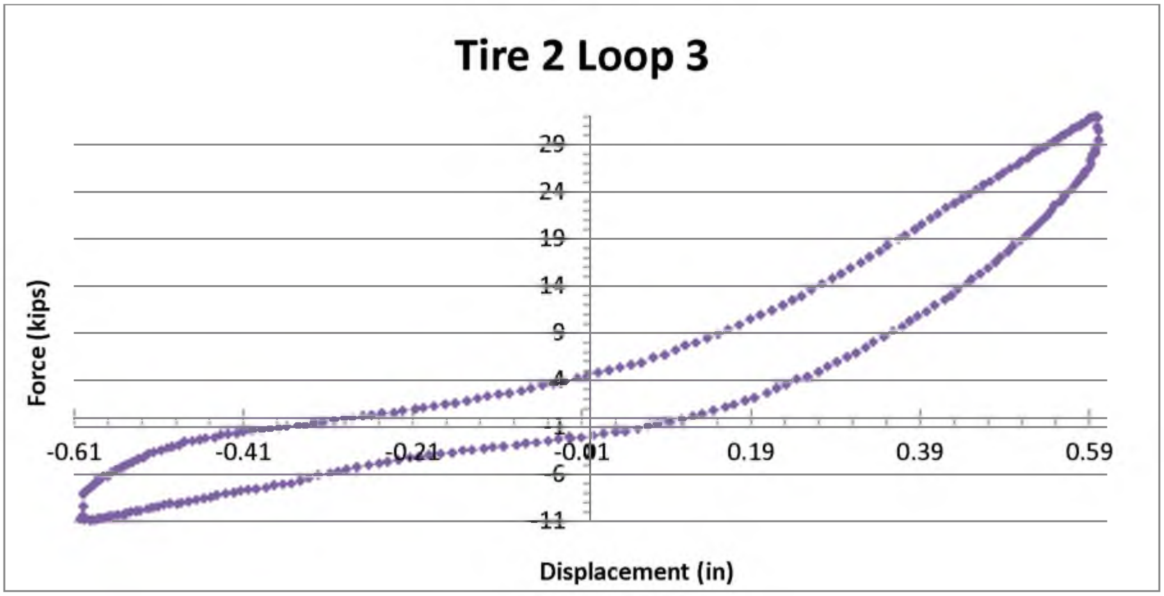

Test 1 Loop 17
27
17
7
-3
-13
-23
-33
Force (kip)
-4.5
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
3.5
4.5
Displacement (in)


Test 1 Loop 18
24
14
4
-6
-16
-26
Force (kip)
-5
-4
-3
-2
-1
0
1
2
3
4
5
Displacement (in)

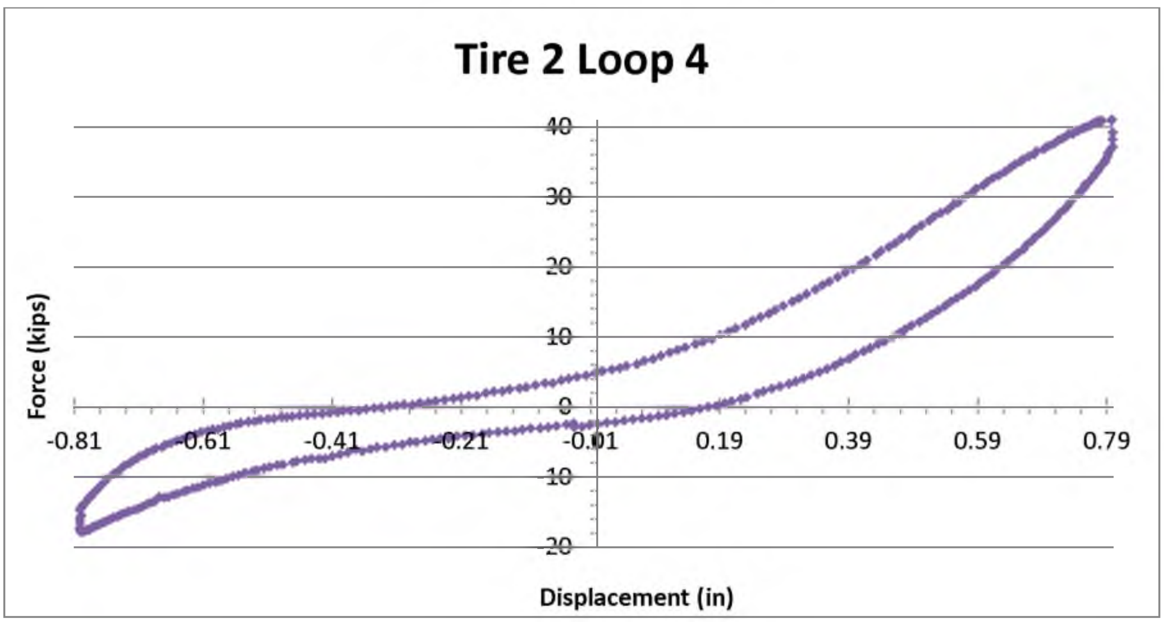
Test Two Individual Loops – 38 Total



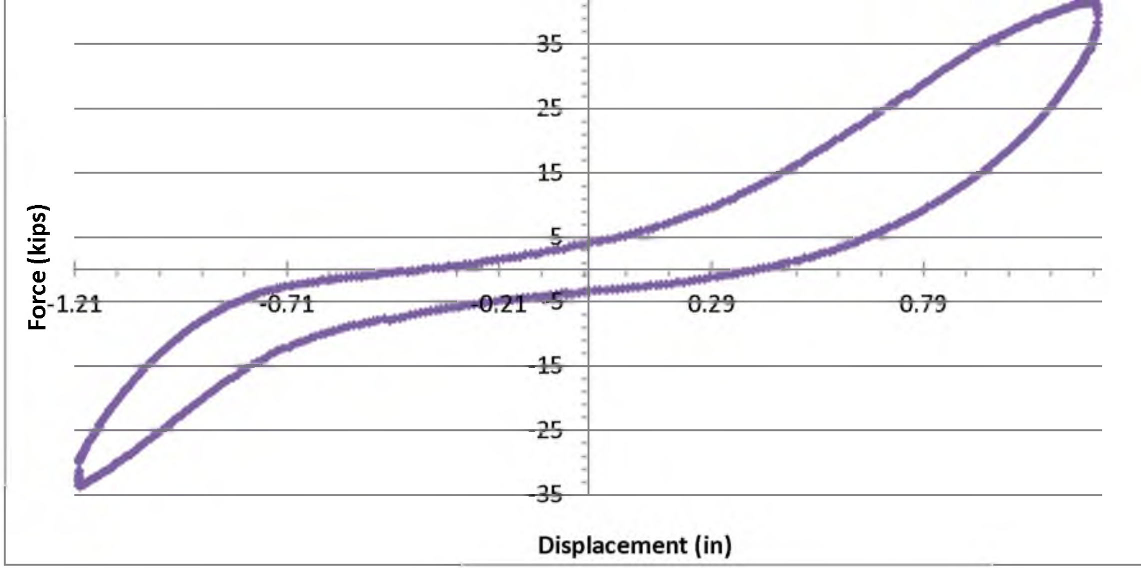




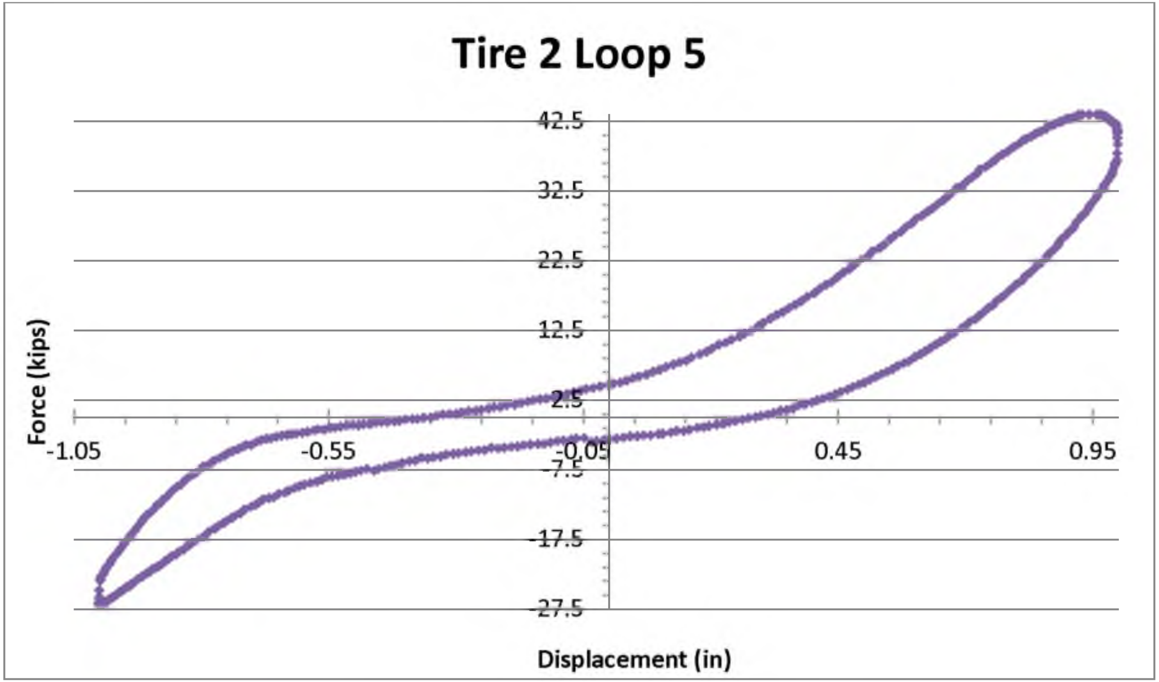
Tire 2 Loop 3
Force (kips)
29
24
19
14
9
4
-1
-6
-11
-0.61
-0.41
-0.21
-0.01
0.19
0.39
0.59
Displacement (in)



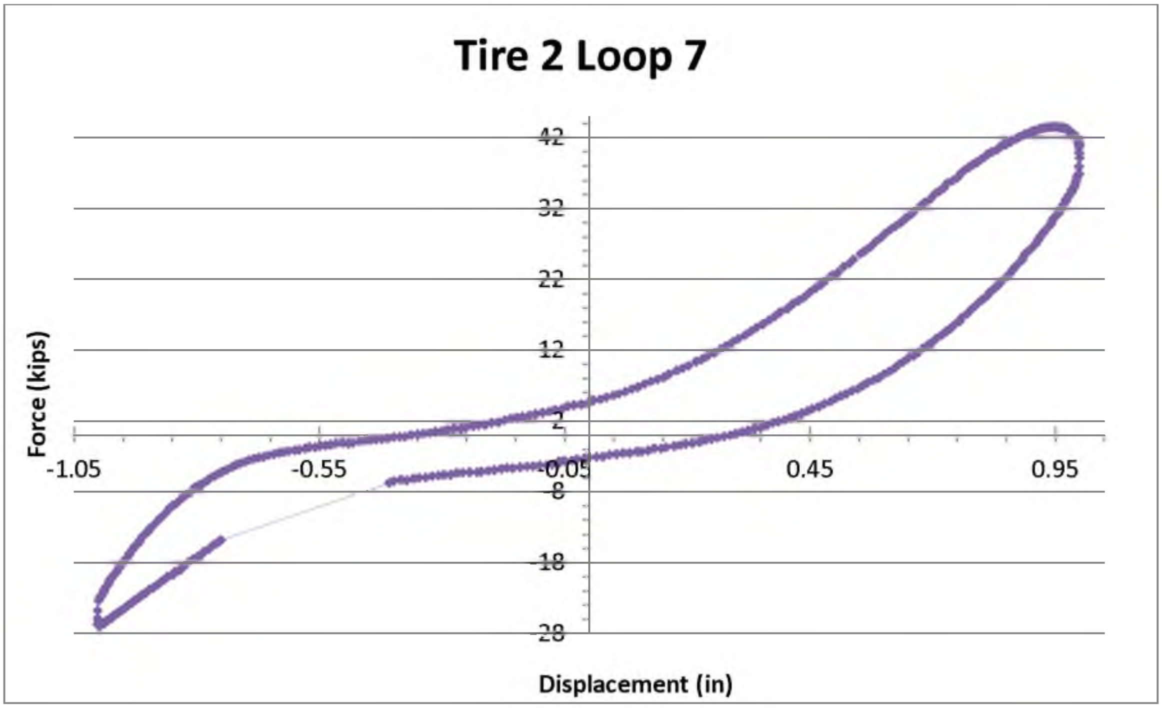
Tire 2 Loop 4
Force (kips)
40
30
20
10
0
-10
-20
-0.81
-0.61
-0.41
-0.21
-0.01
0.19
0.39
0.59
0.79
Displacement (in)



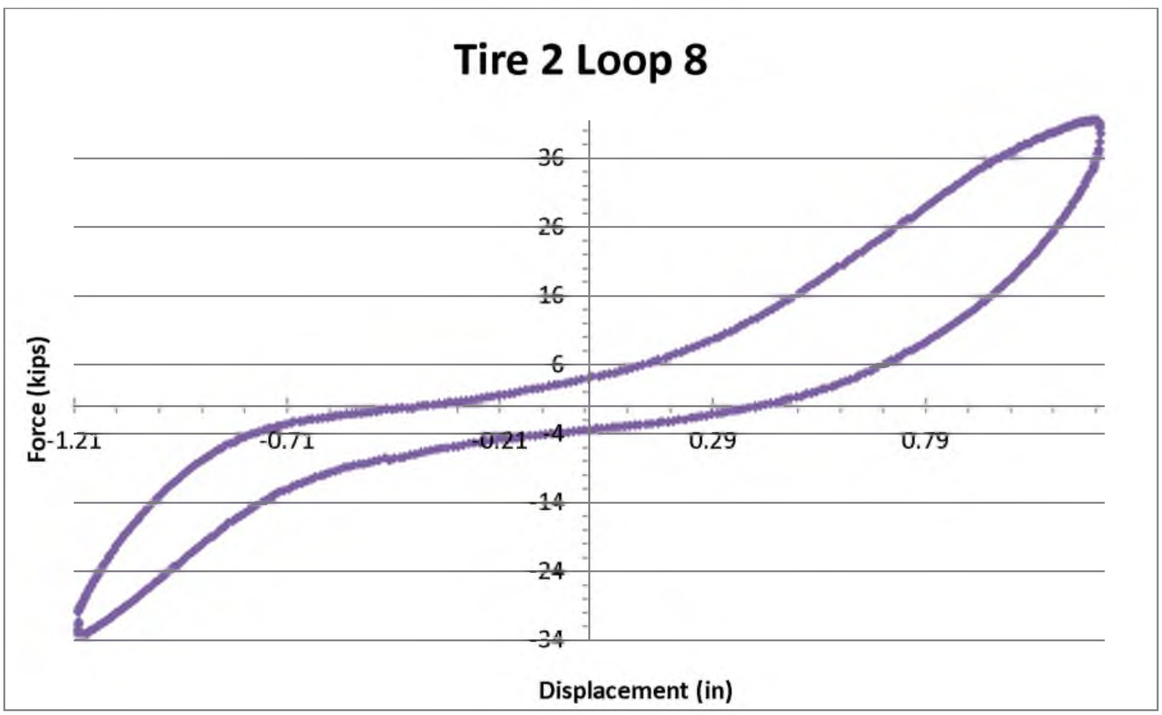
Force (kips)
35
25
15
5
-5
-15
-25
-35
-1.21
-0.71
-0.21
0.29
0.79
Displacement (in)


Tire 2 Loop 5
42.5
32.5
22.5
12.5
2.5
-7.5
-17.5
-27.5
Force (kips)
-1.05
-0.55
-0.05
0.45
0.95
Displacement (in)

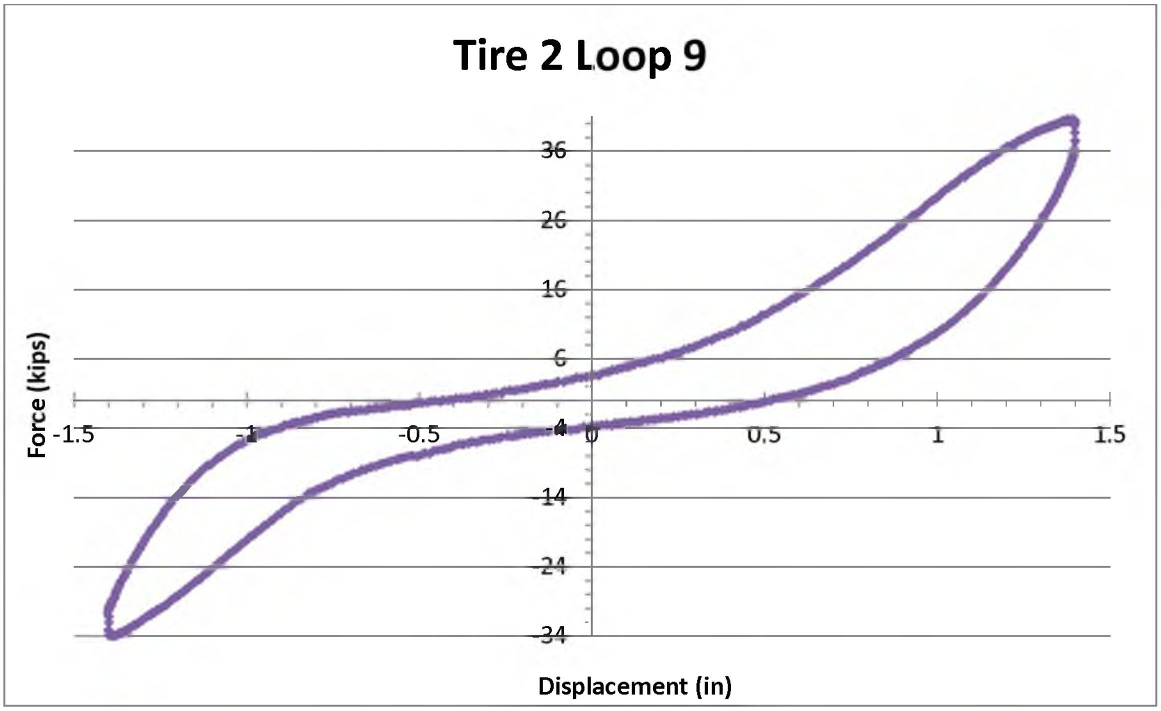

Tire 2 Loop 6

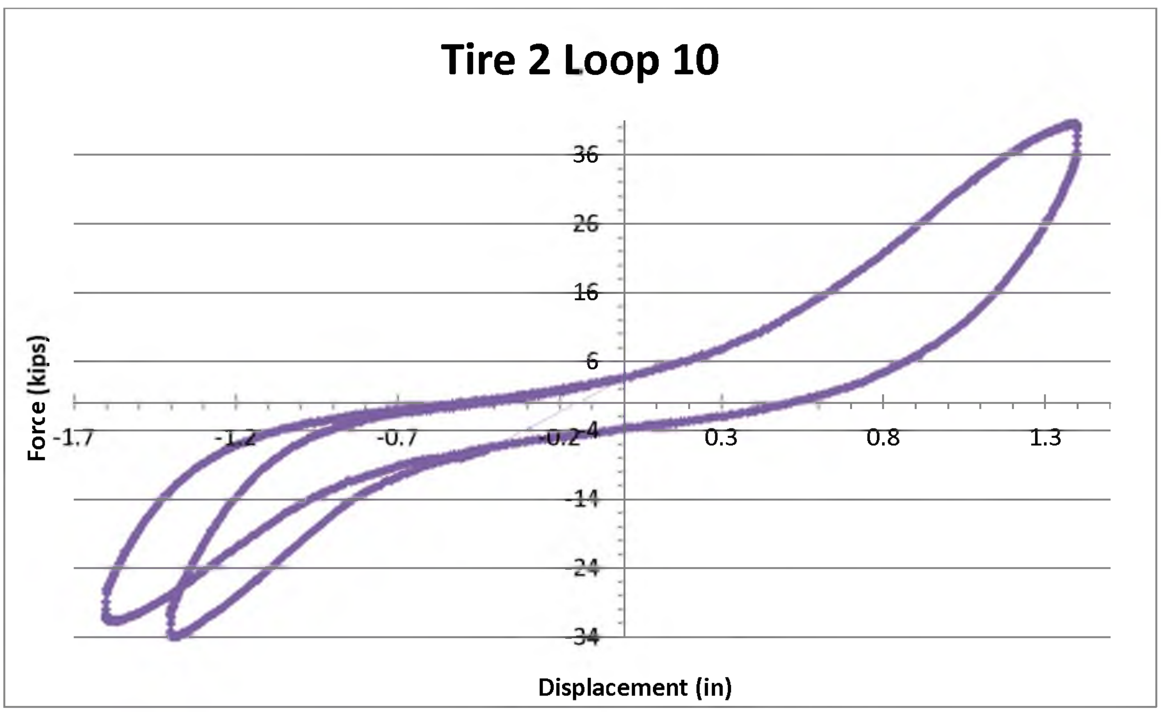


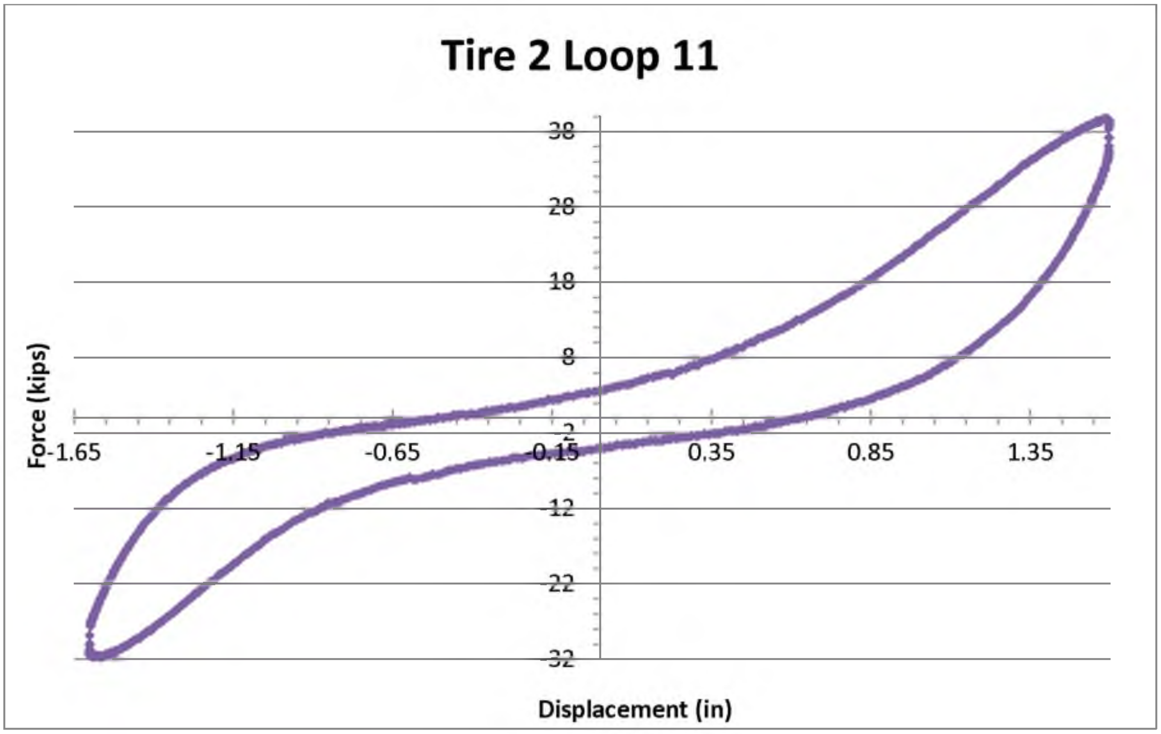
Tire 2 Loop 7
42
32
22
12
2
-8
-18
-28
-1.05
-0.55
-0.05
0.45
0.95
Force (kips)
Displacement (in)

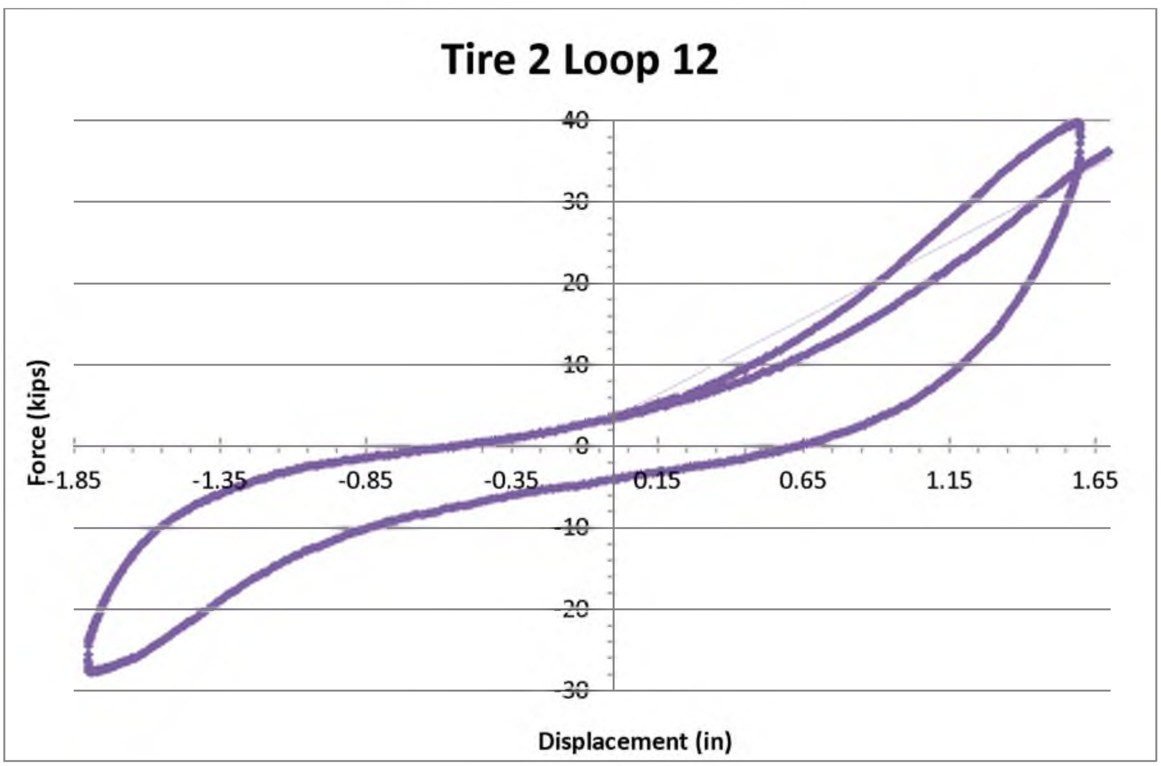


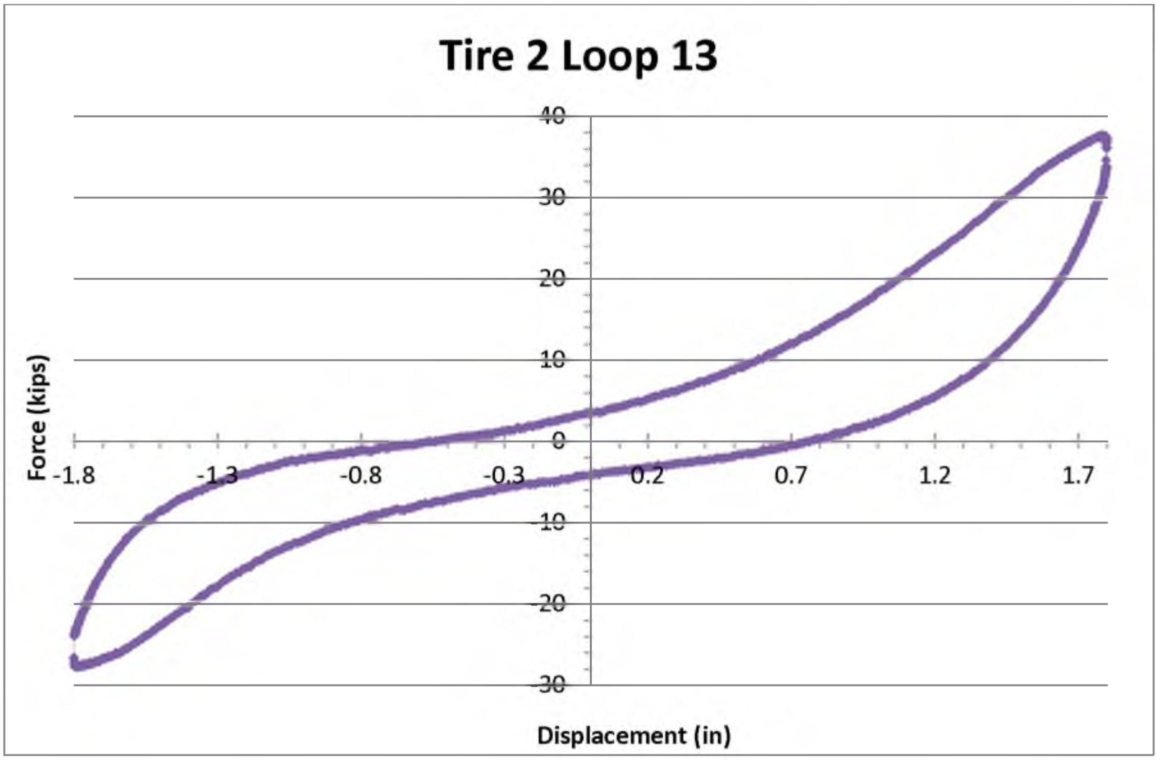
Tire 2 Loop 8
36
26
16
6
-4
-14
-24
-34
-1.21
-0.71
-0.21
0.29
0.79
Force (kips)
Displacement (in)

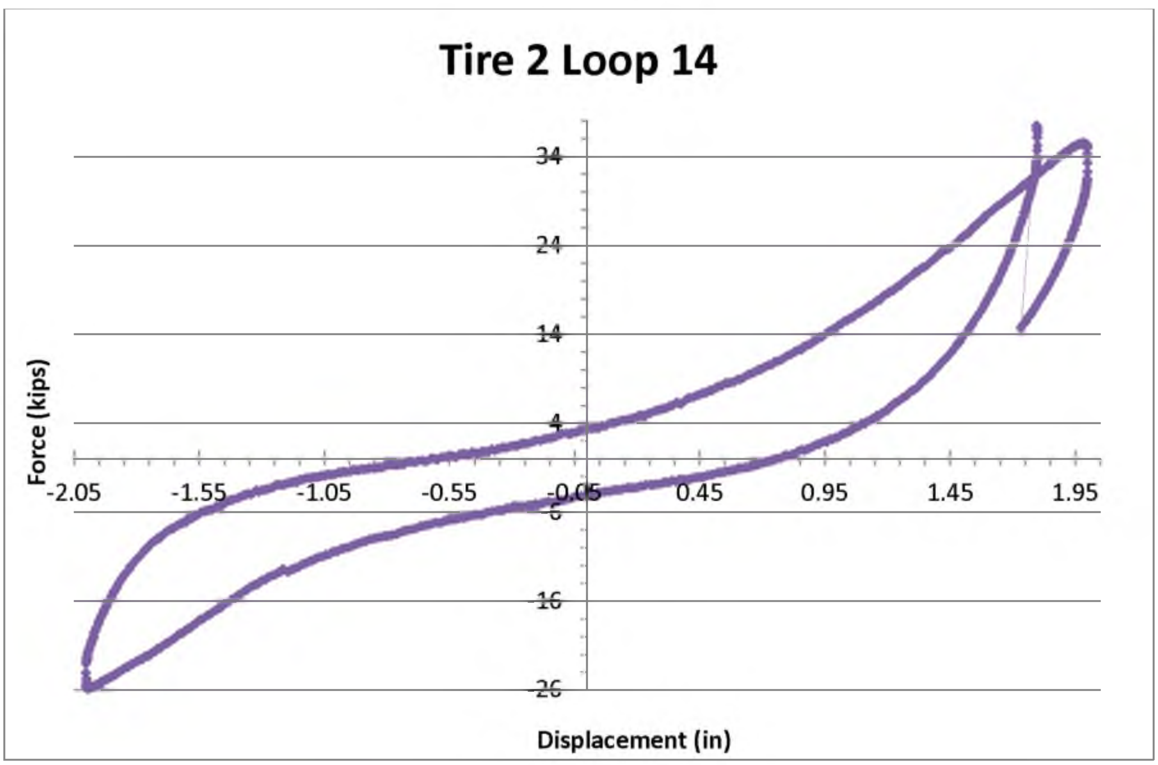

Tire 2 Loop 9
36
26
16
6
-4
-14
-24
-34
-1.5
-1
-0.5
0
0.5
1
1.5
Force (kips)
Displacement (in)

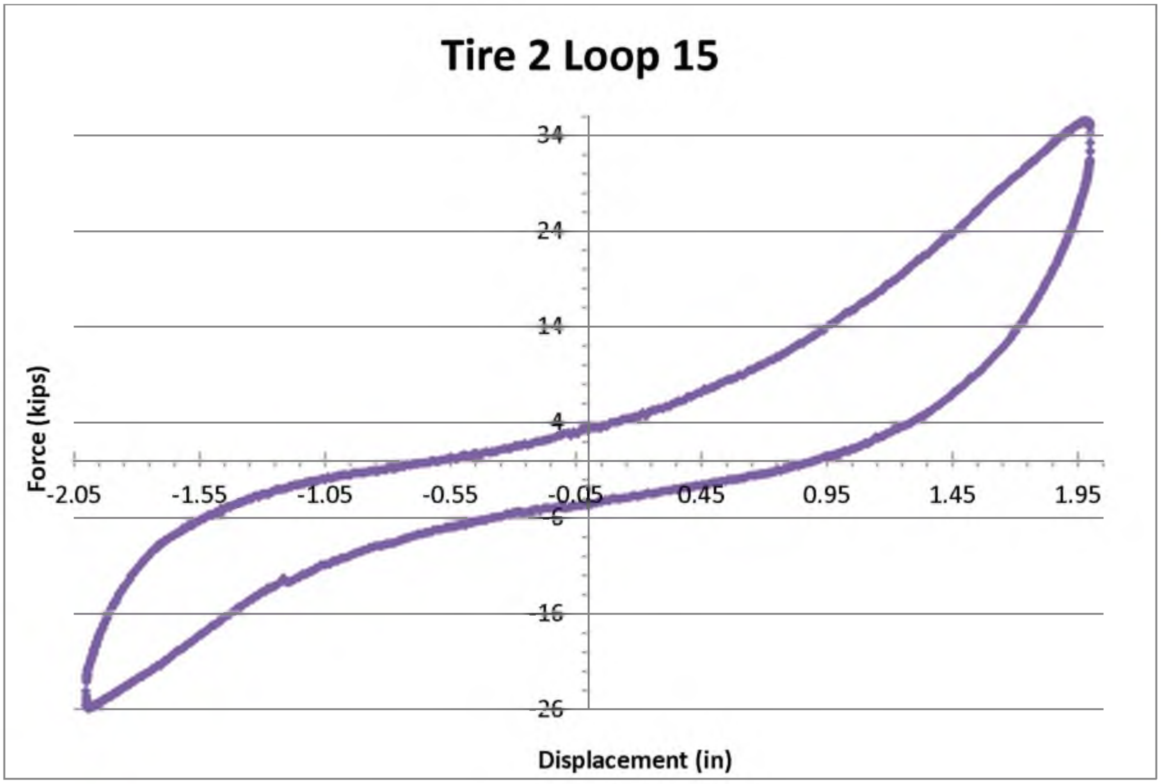

Tire 2 Loop 10
36
26
16
6
-4
-14
-24
-34
-1.7
-1.2
-0.7
-0.2
0.3
0.8
1.3
Force (kips)
Displacement (in)


Tire 2 Loop 11
38
28
18
8
-2
-12
-22
-32
-1.65
-1.15
-0.65
-0.15
0.35
0.85
1.35
Force (kips)
Displacement (in)

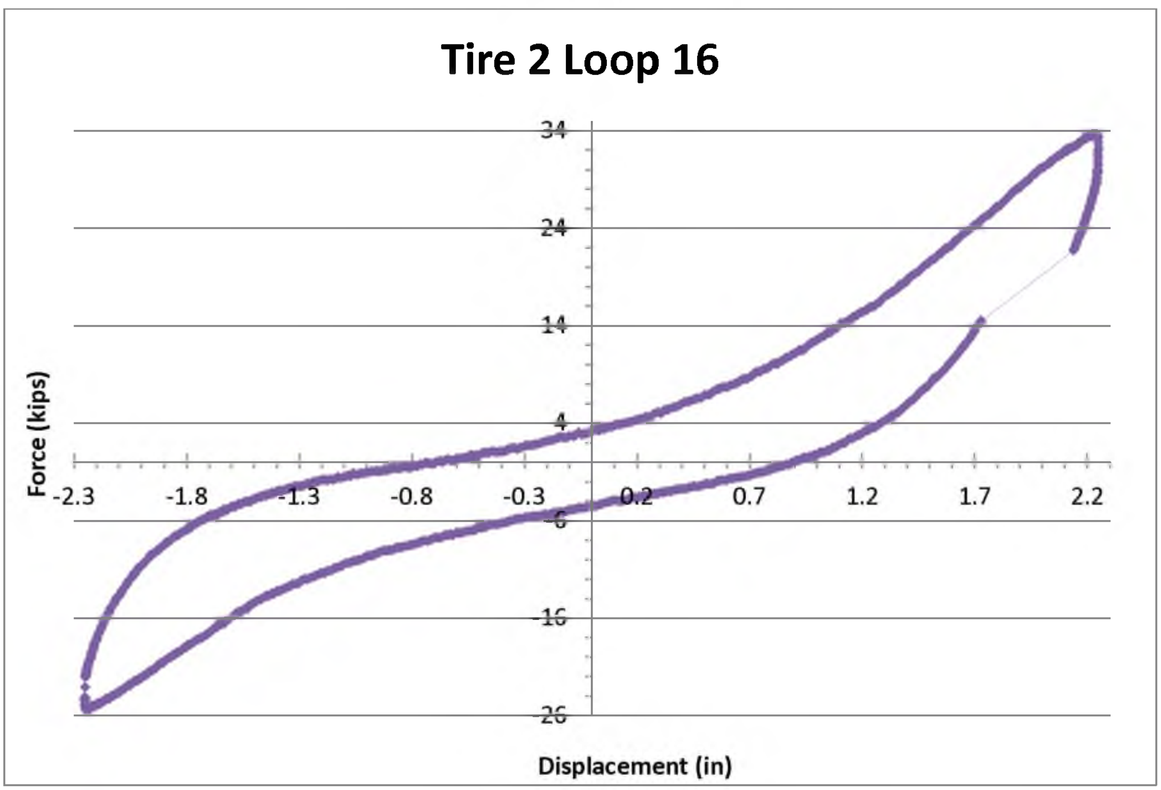

Tire 2 Loop 12
40
30
20
10
0
-10
-20
-30
-1.85
-1.35
-0.85
-0.35
0.15
0.65
1.15
1.65
Force (kips)
Displacement (in)


Tire 2 Loop 13
40
30
20
10
0
-10
-20
-30
-1.8
-1.3
-0.8
-0.3
0.2
0.7
1.2
1.7
Force (kips)
Displacement (in)

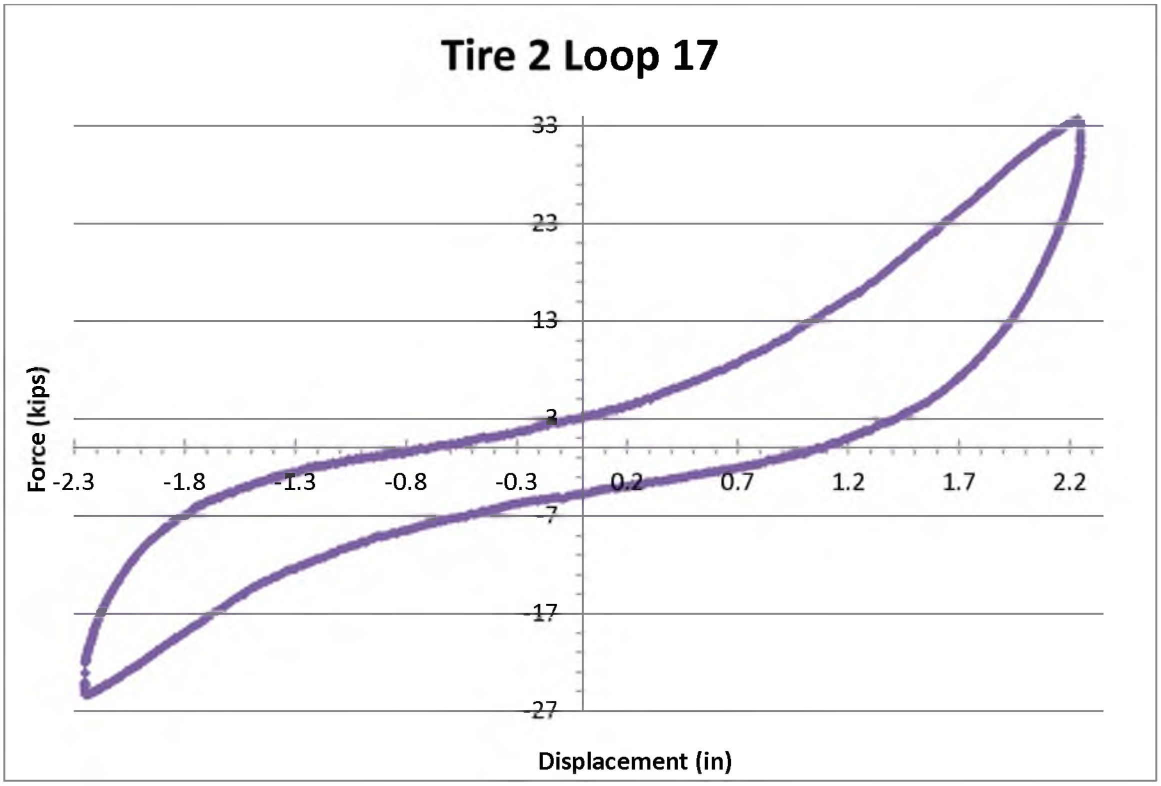

Tire 2 Loop 14
34
24
14
4
-6
-16
-26
-2.05
-1.55
-1.05
-0.55
-0.05
0.45
0.95
1.45
1.95
Force (kips)
Displacement (in)

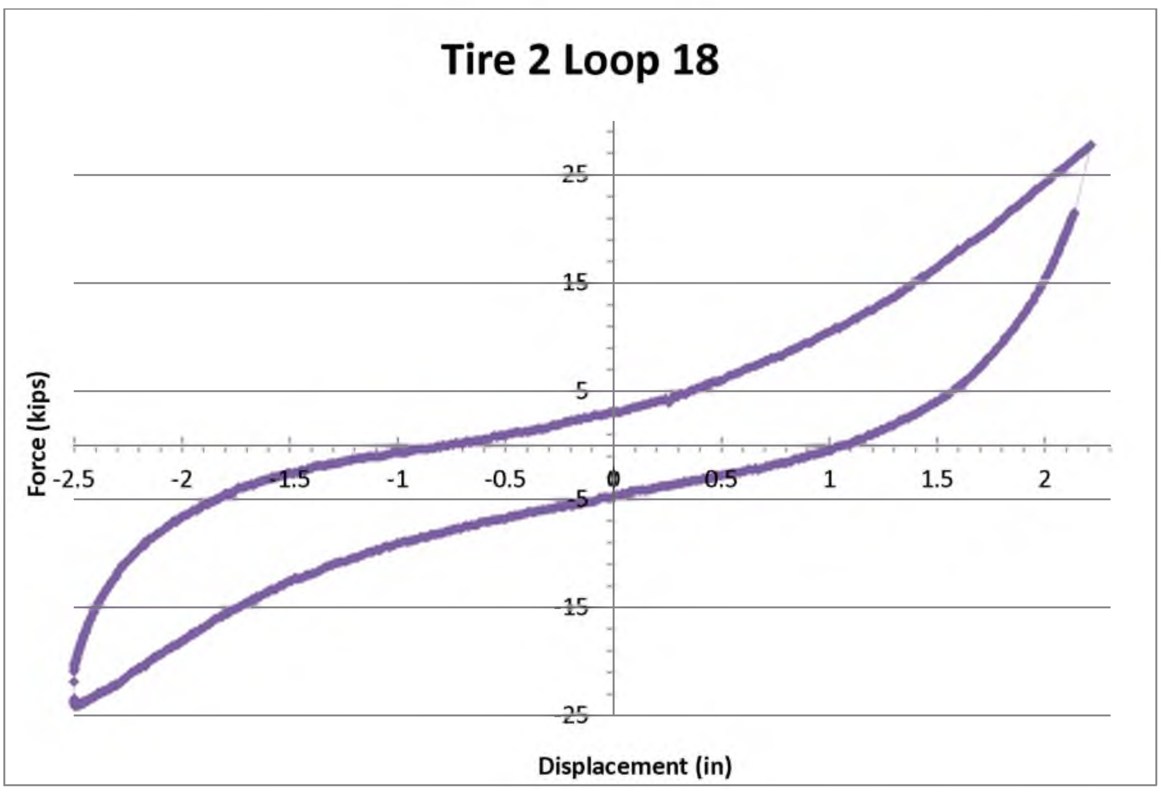


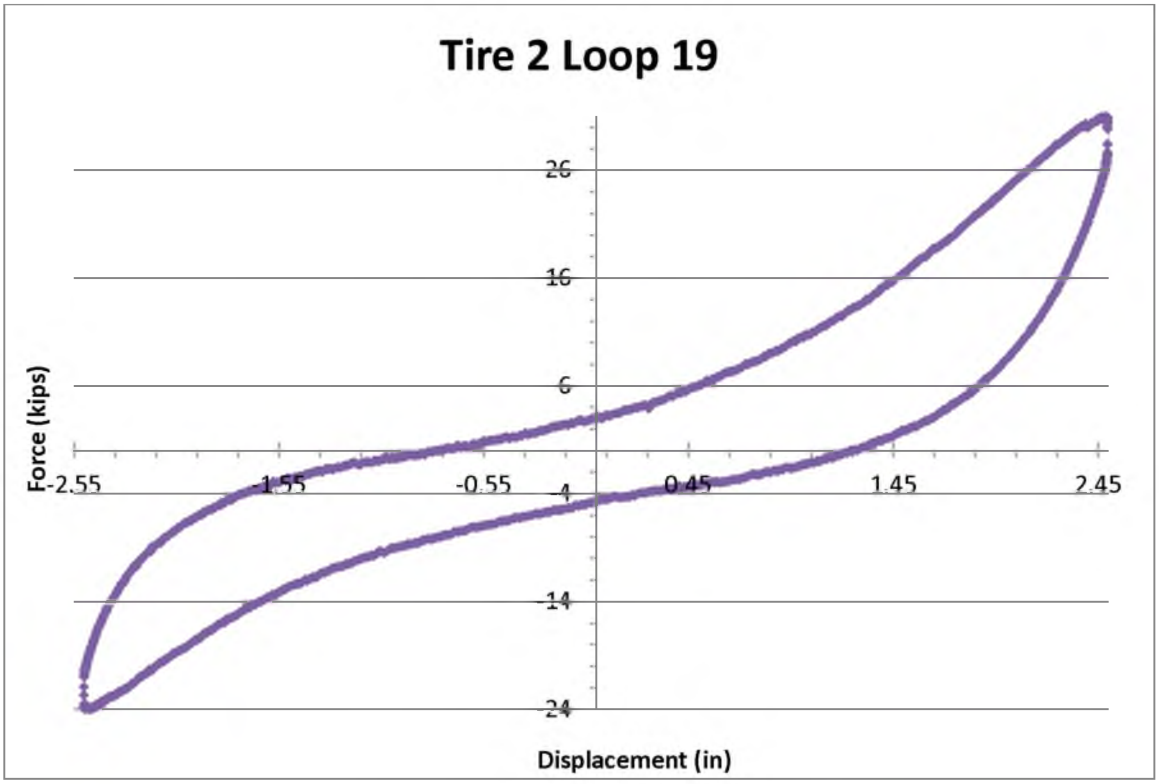
Tire 2 Loop 15
34
24
14
4
-6
-16
-26
-2.05
-1.55
-1.05
-0.55
-0.05
0.45
0.95
1.45
1.95
Force (kips)
Displacement (in)

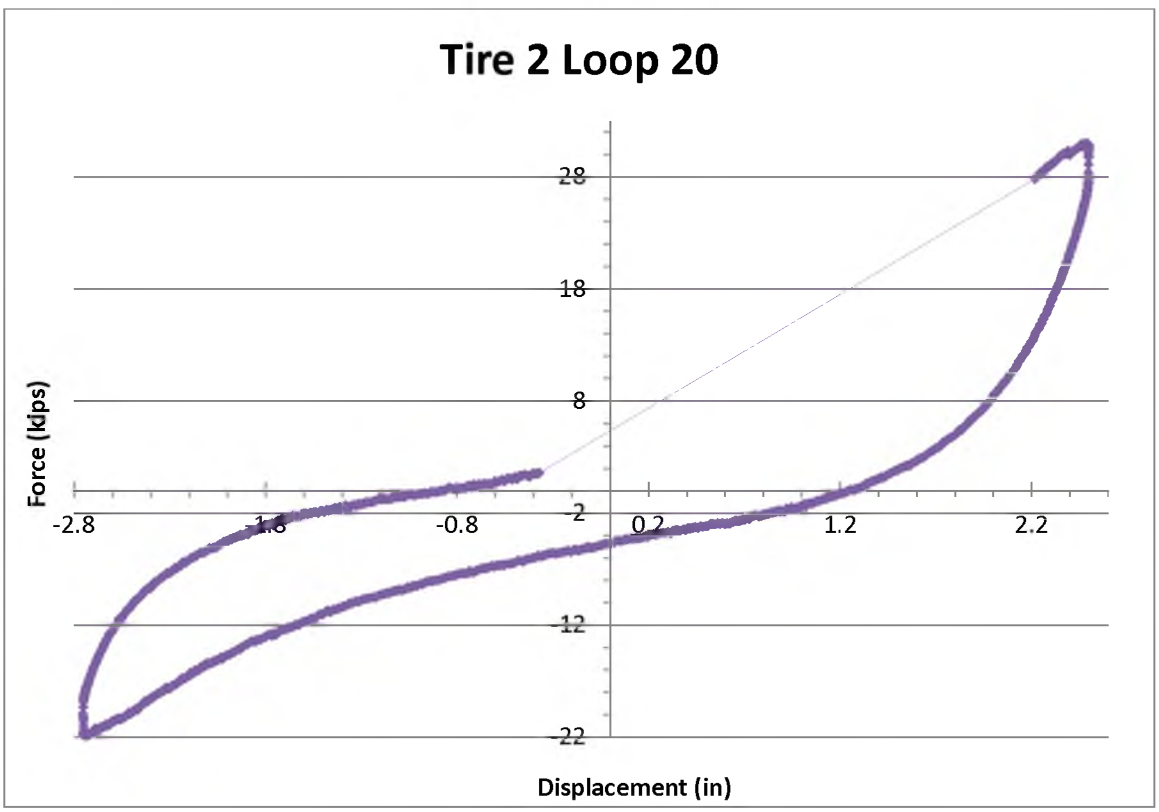


Tire 2 Loop 16
34
24
14
4
-6
-16
-26
-2.3
-1.8
-1.3
-0.8
-0.3
0.2
0.7
1.2
1.7
2.2
Force (kips)
Displacement (in)

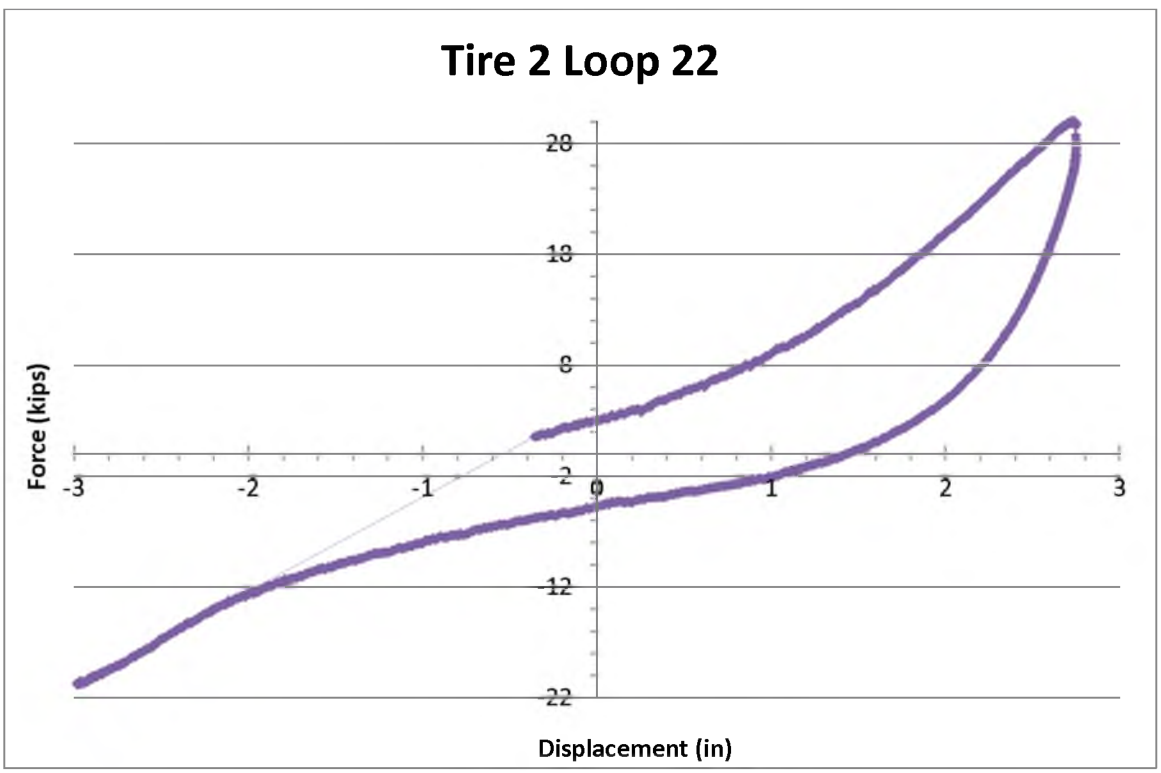

Tire 2 Loop 17
33
23
13
3
-7
-17
-27
-2.3
-1.8
-1.3
-0.8
-0.3
0.2
0.7
1.2
1.7
2.2
Force (kips)
Displacement (in)

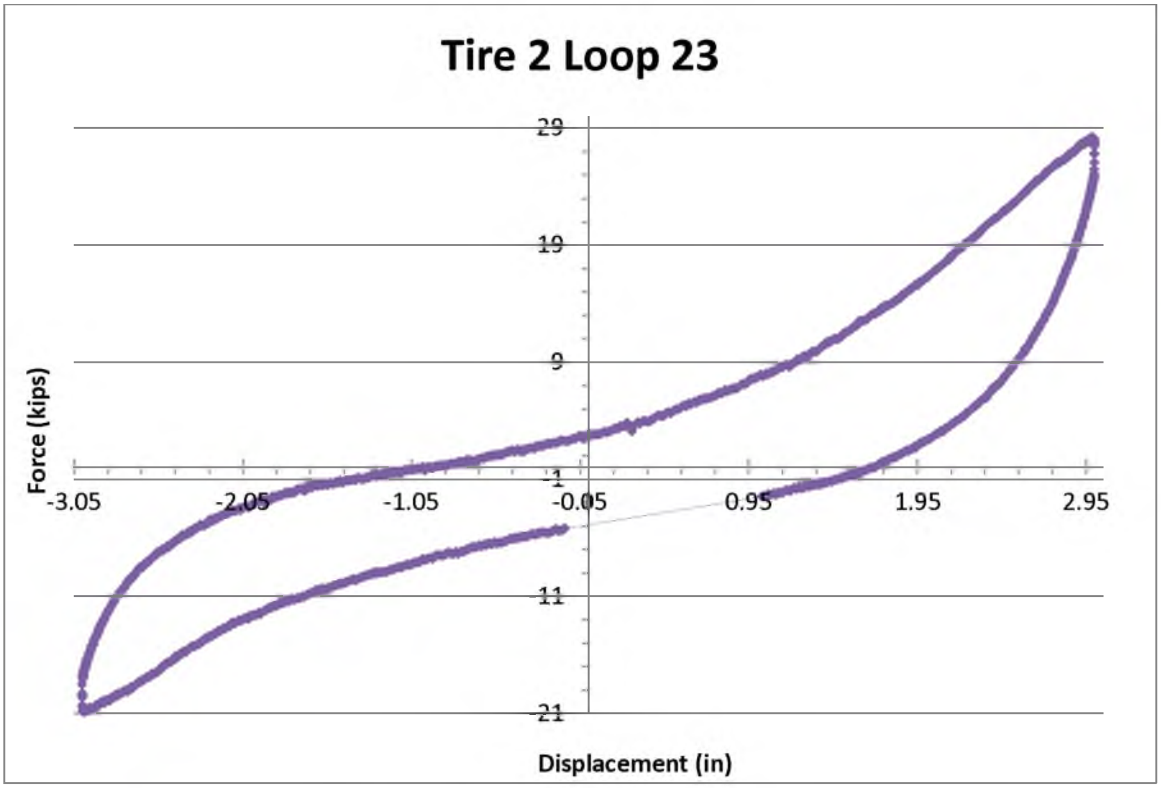

Tire 2 Loop 18
25
15
5
-5
-15
-25
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Force (kips)
Displacement (in)

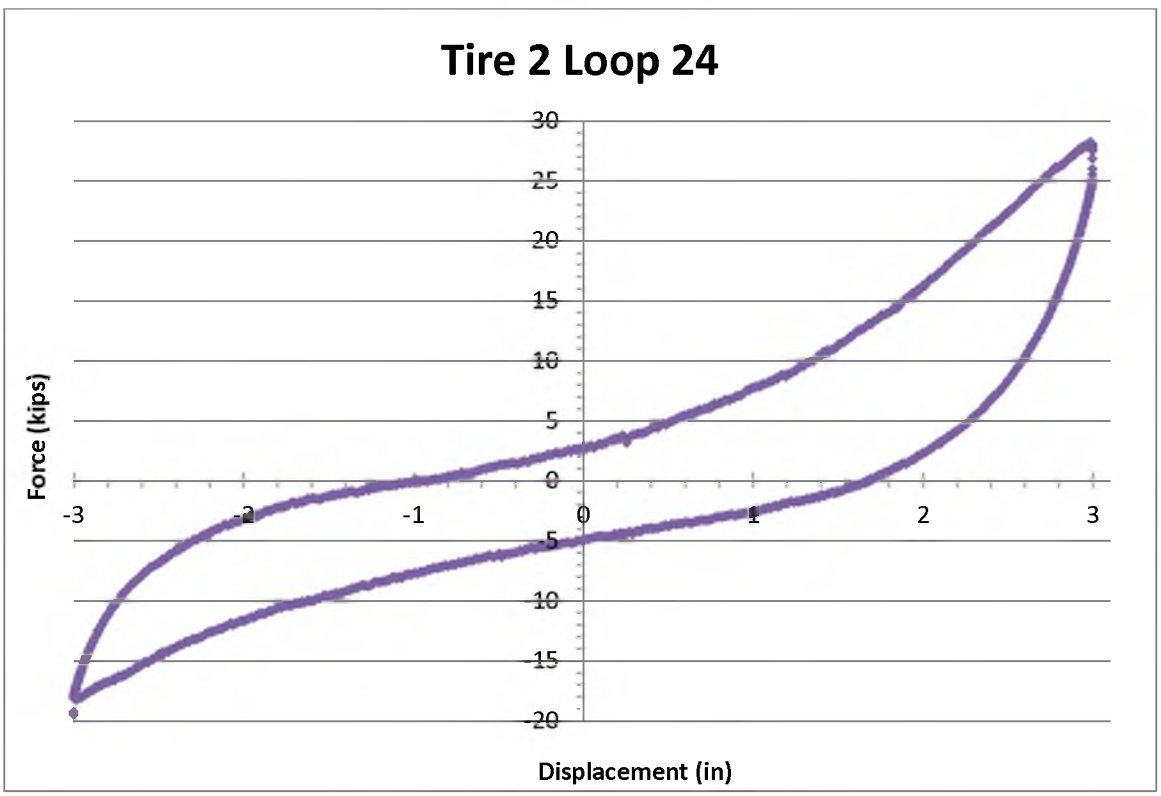

Tire 2 Loop 19
Force (kips)
Displacement (in)
26
16
6
-4
-14
-24
-2.55
-1.55
-0.55
0.45
1.45
2.45

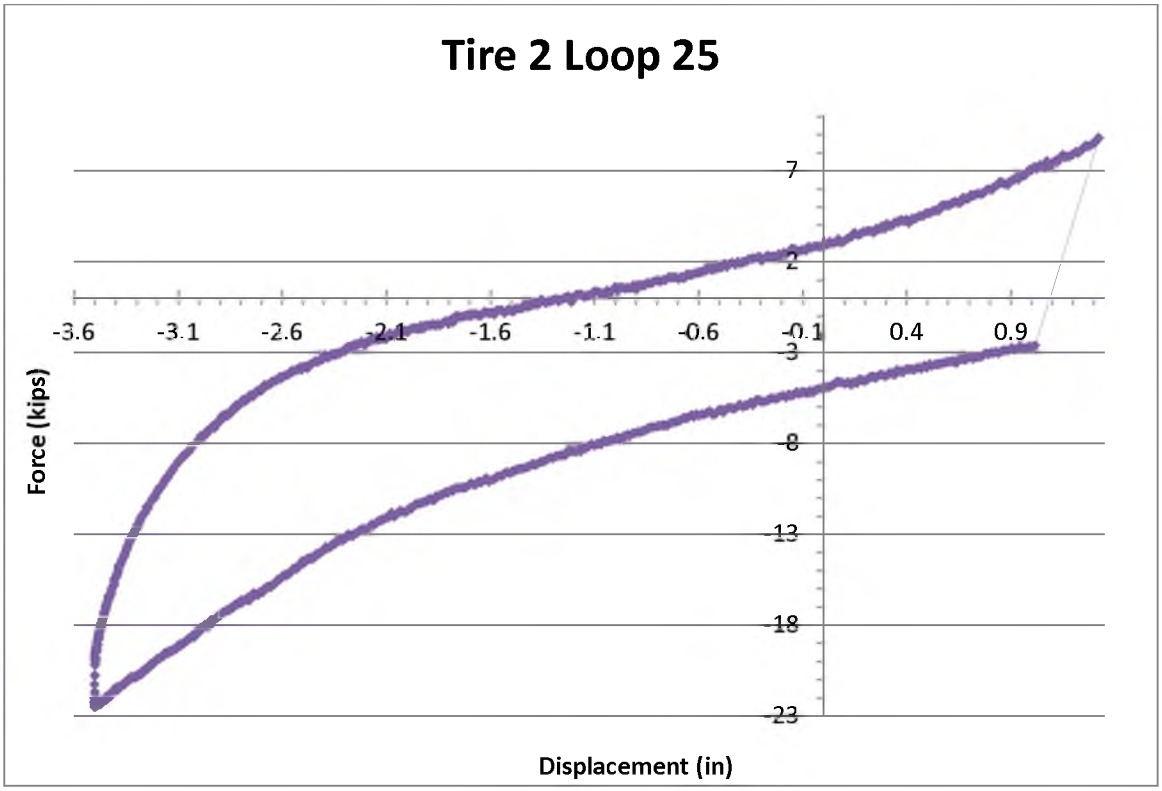

Tire 2 Loop 20
Force (kips)
Displacement (in)
28
18
8
-2
-12
-22
-2.8
-1.8
-0.8
0.2
1.2
2.2

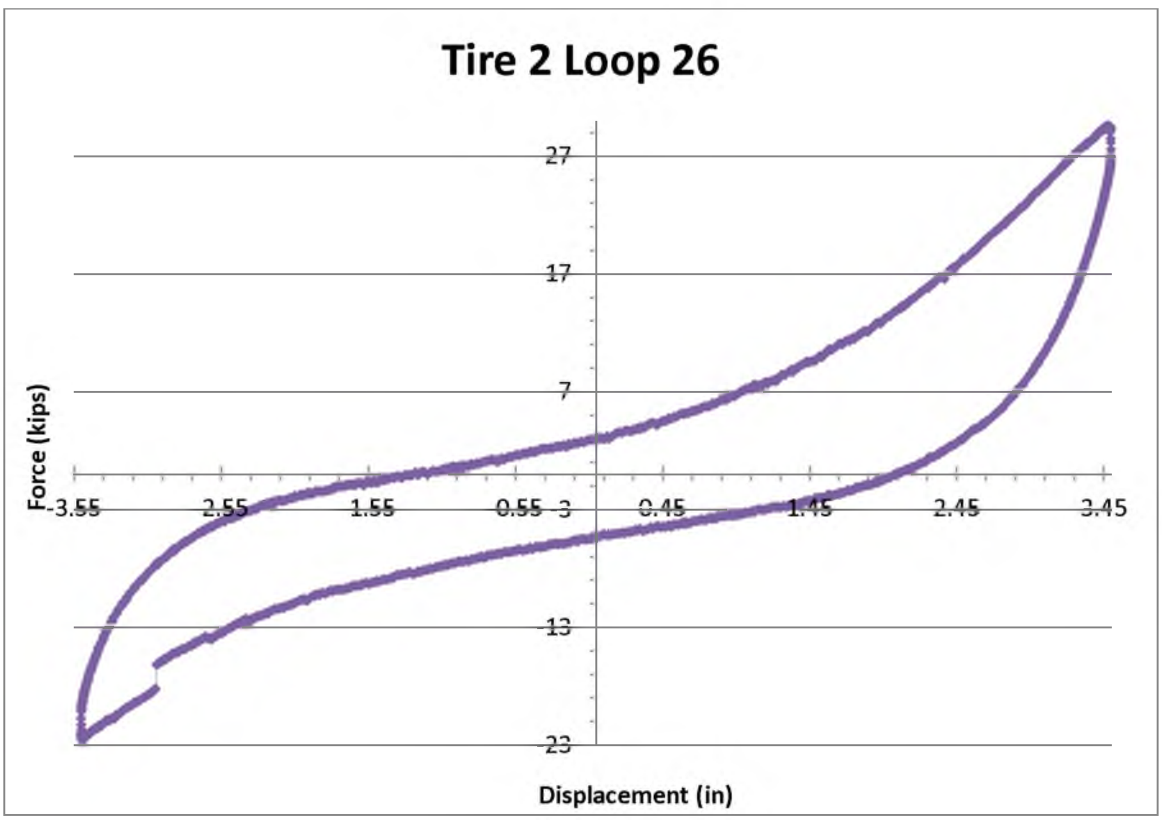

Tire 2 Loop 21
Force (kips)
28
18
8
-2
-12
-22
-2.8
-1.8
-0.8
0.2
1.2
2.2
Displacement (in)


Tire 2 Loop 22
Force (kips)
28
18
8
-2
-12
-22
-3
-2
-1
0
1
2
3
Displacement (in)

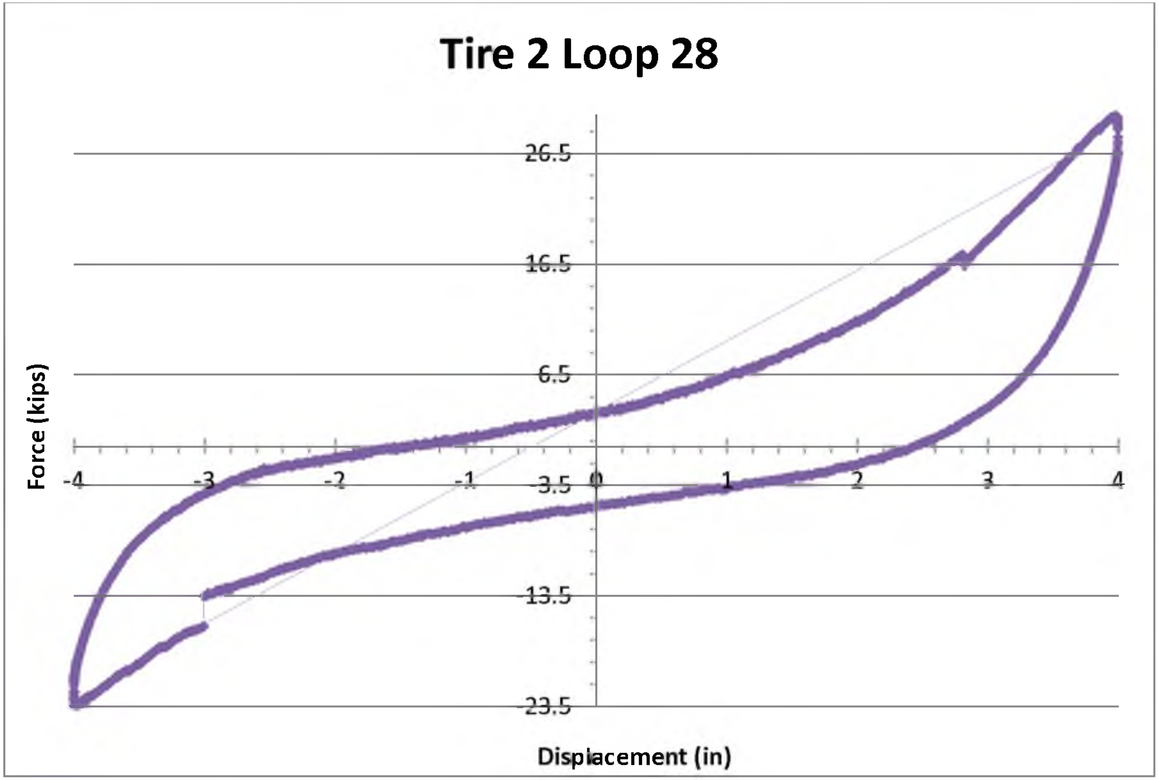

Tire 2 Loop 23
29
19
9
-1
-11
-21
-3.05
-2.05
-1.05
-0.05
0.95
1.95
2.95
Force (kips)
Displacement (in)

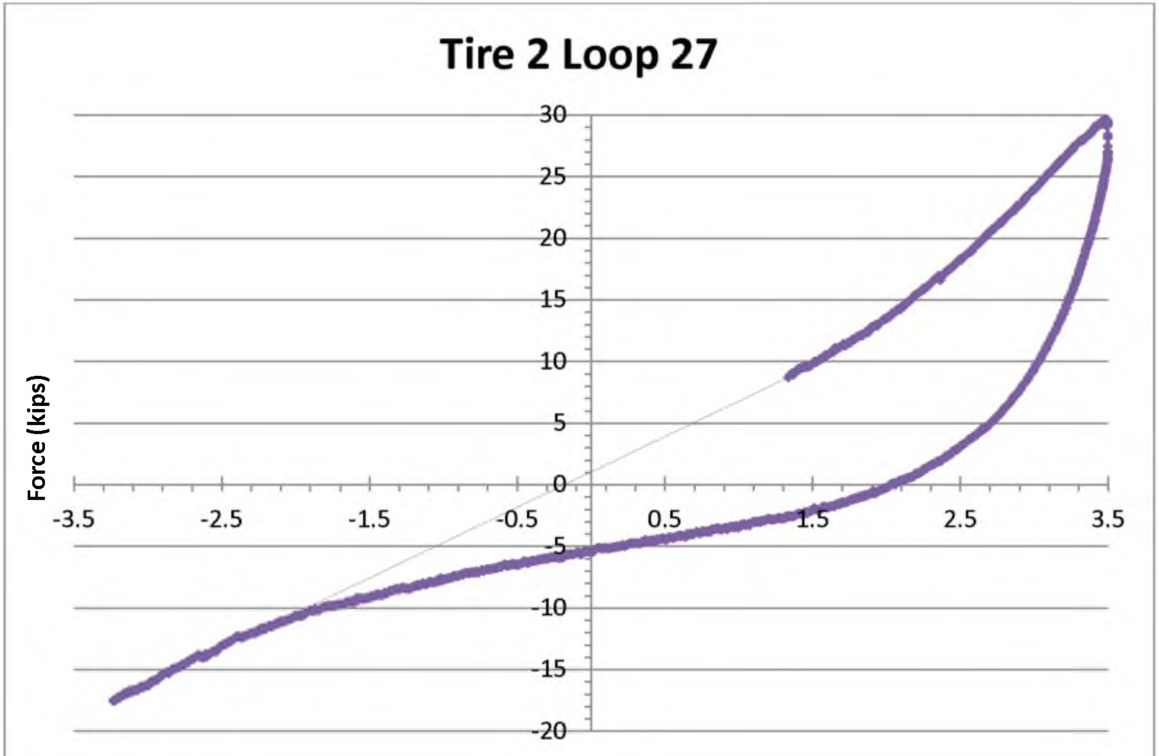

Tire 2 Loop 24
30
25
20
15
10
5
0
-5
-10
-15
-20
-3
-2
-1
0
1
2
3
Force (kips)
Displacement (in)

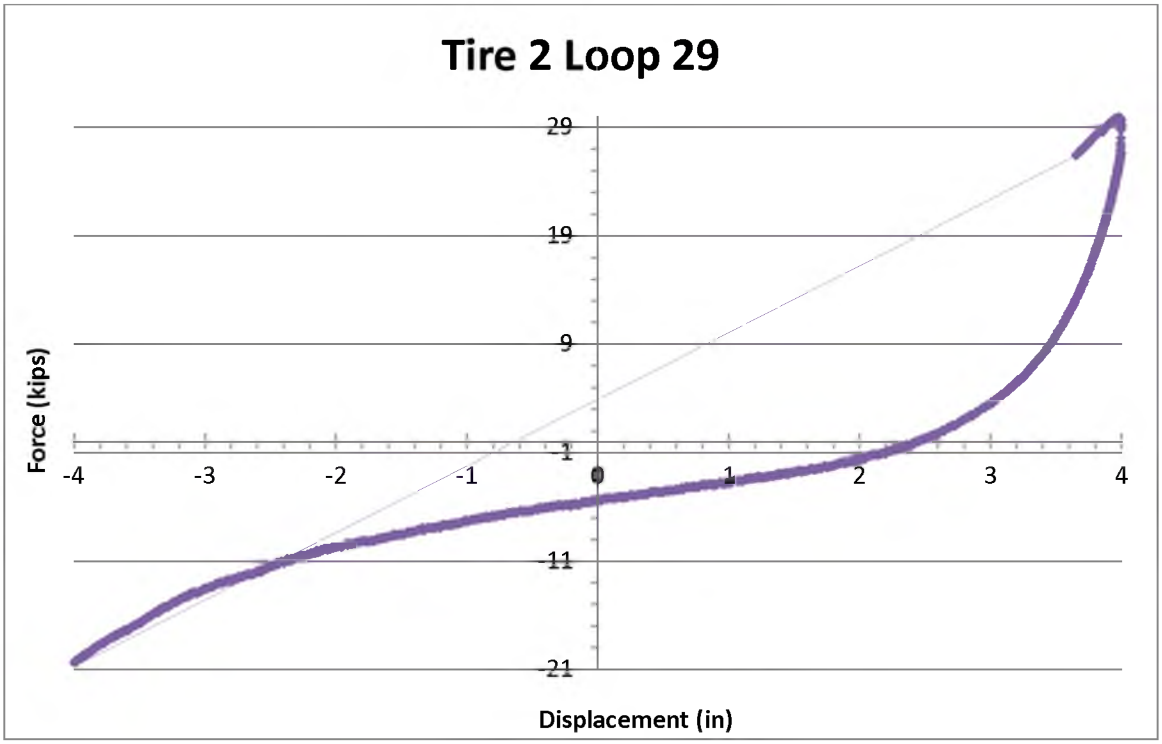

Tire 2 Loop 25
7
2
-3
-8
-13
-18
-23
-3.6
-3.1
-2.6
-2.1
-1.6
-1.1
-0.6
-0.1
0.4
0.9
Force (kips)
Displacement (in)

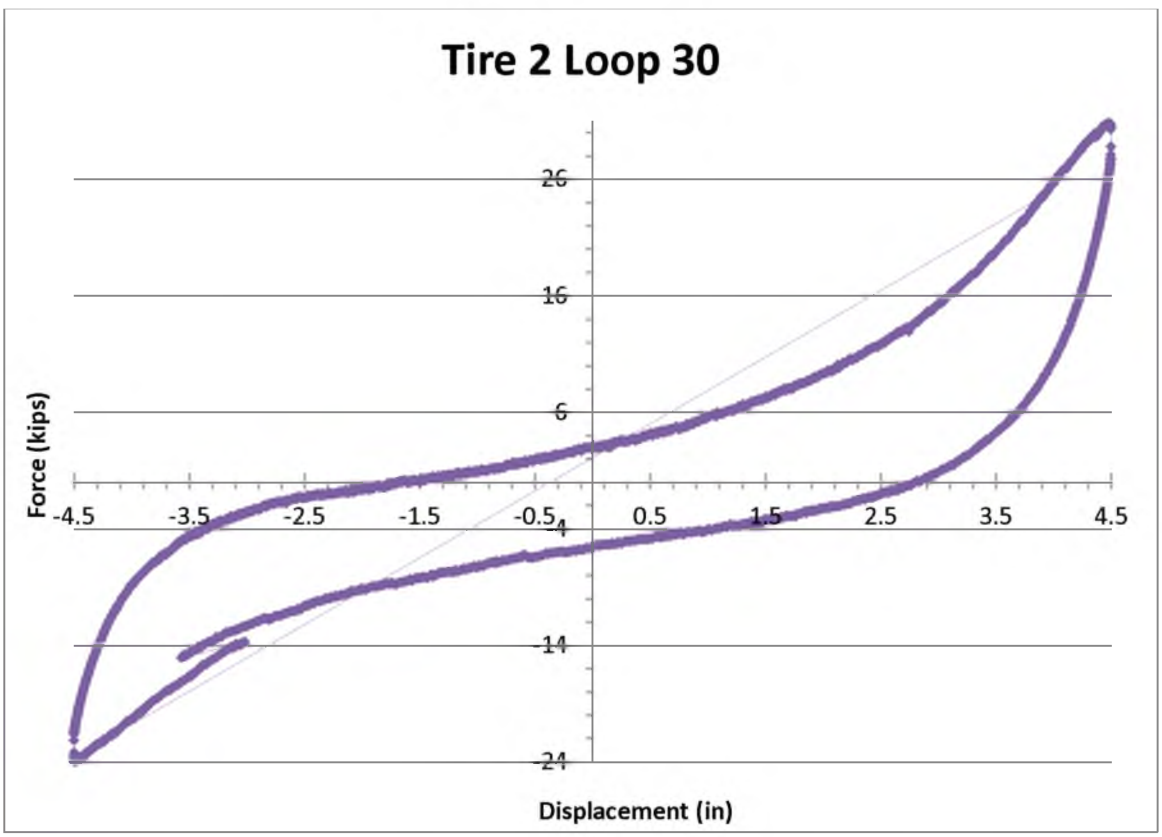

Tire 2 Loop 26
27
17
7
-3
-13
-23
-3.55
-2.55
-1.55
-0.55
0.45
1.45
2.45
3.45
Force (kips)
Displacement (in)

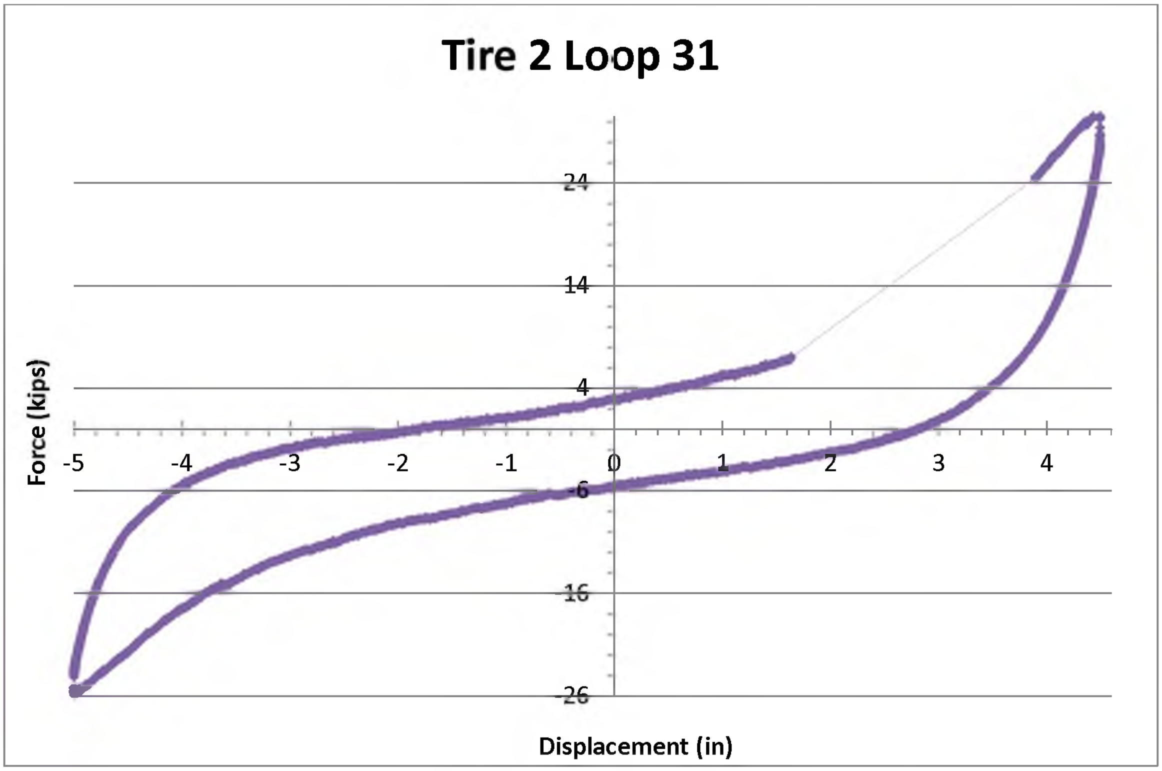
Displacement (in)

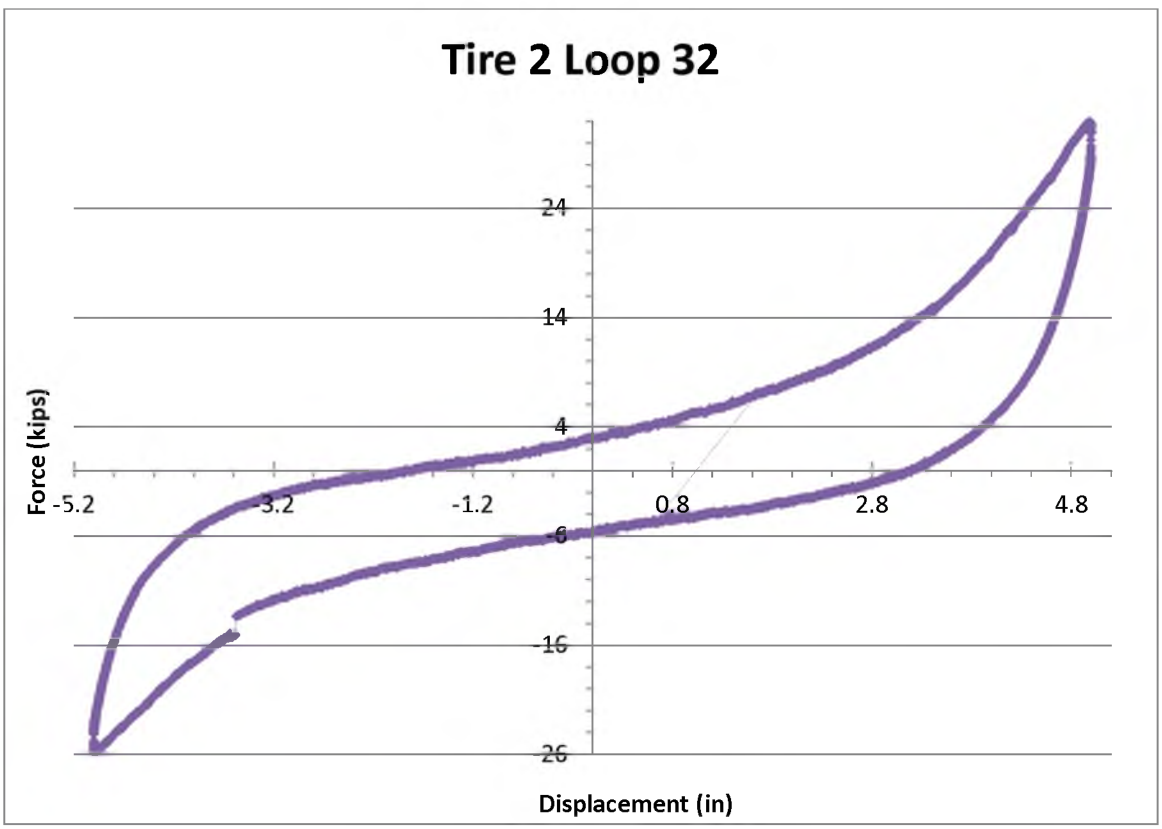


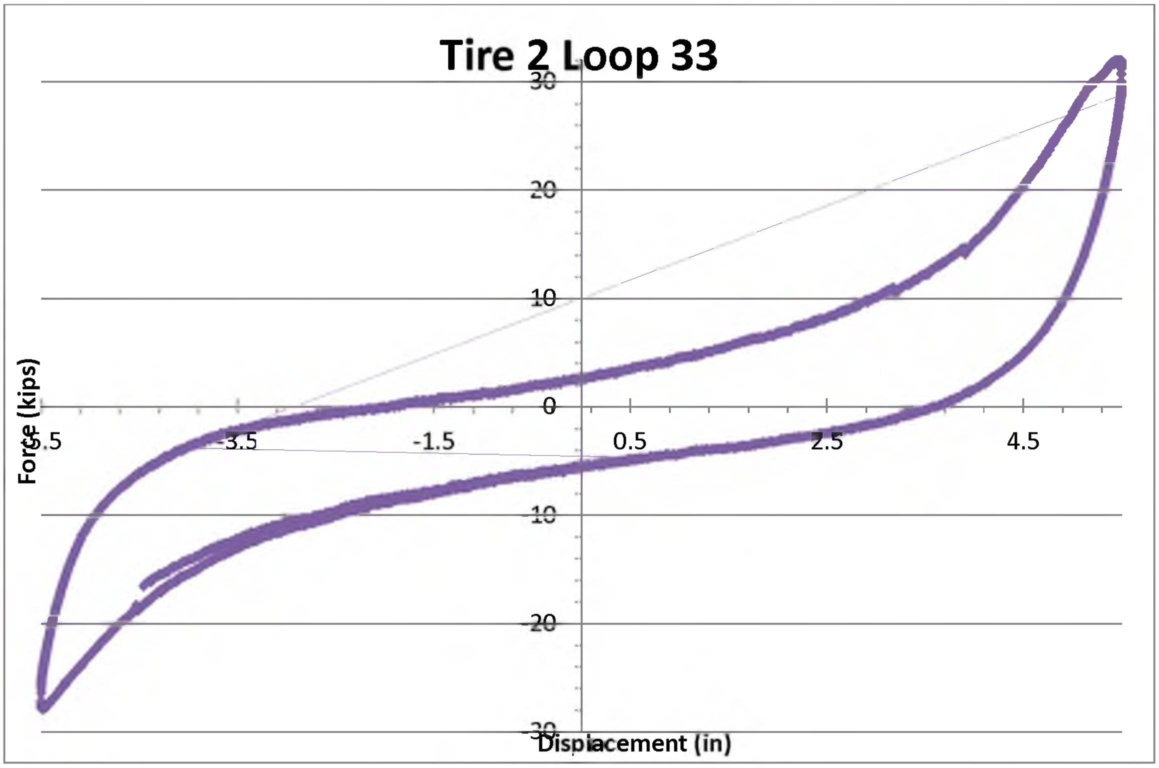

Tire 2 Loop 27
Force (kips)
30
25
20
15
10
5
0
-5
-10
-15
-20
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
3.5

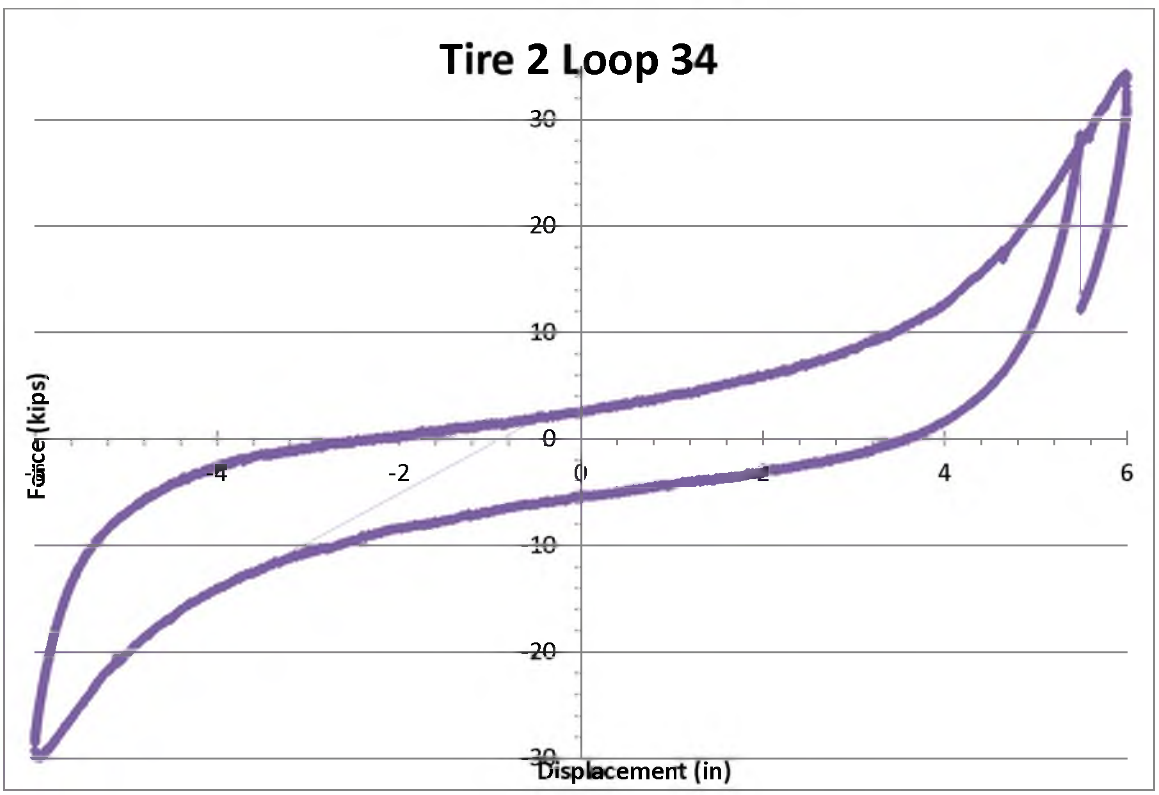

Tire 2 Loop 29
29
19
9
-1
-11
-21
-4
-3
-2
-1
0
1
2
3
4
Force (kips)
Displacement (in)

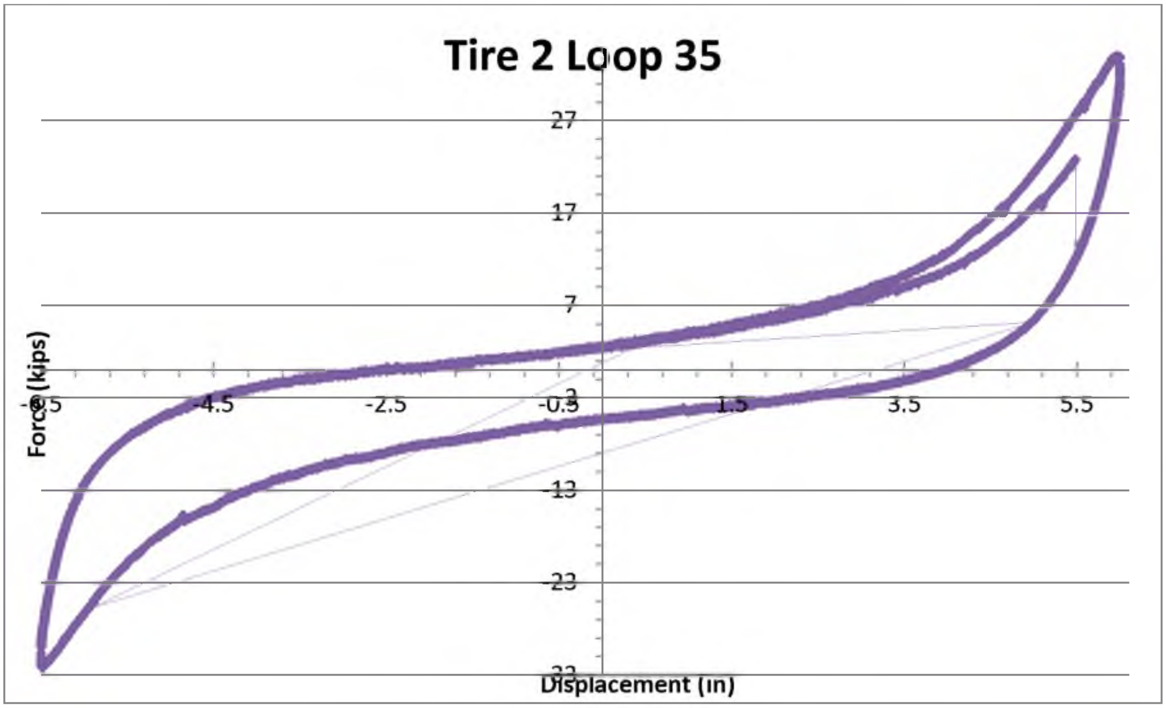

Tire 2 Loop 30
26
16
6
-4
-14
-24
-4.5
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
3.5
4.5
Force (kips)
Displacement (in)

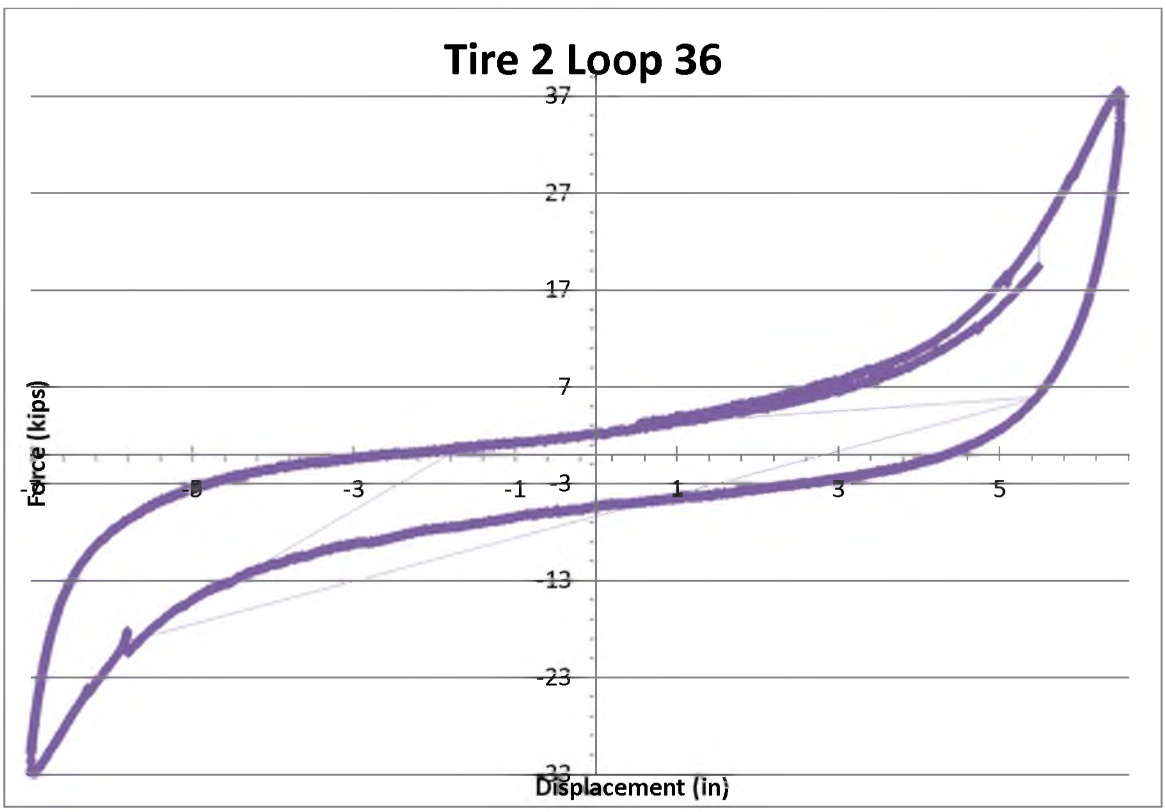

Tire 2 Loop 31
24
14
4
-6
-16
-26
-5
-4
-3
-2
-1
0
1
2
3
4
Force (kips)
Displacement (in)

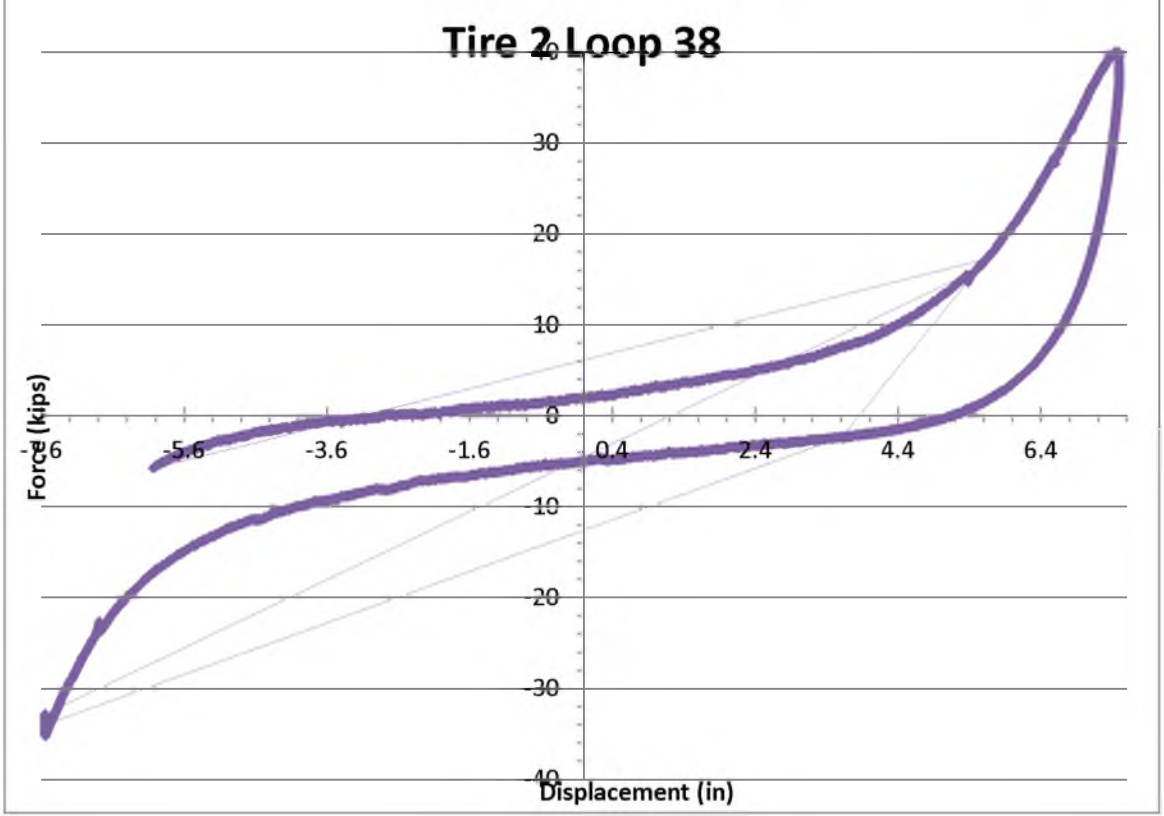

Tire 2 Loop 32
24
14
4
-6
-16
-26
-5.2
-3.2
-1.2
0.8
2.8
4.8
Force (kips)
Displacement (in)

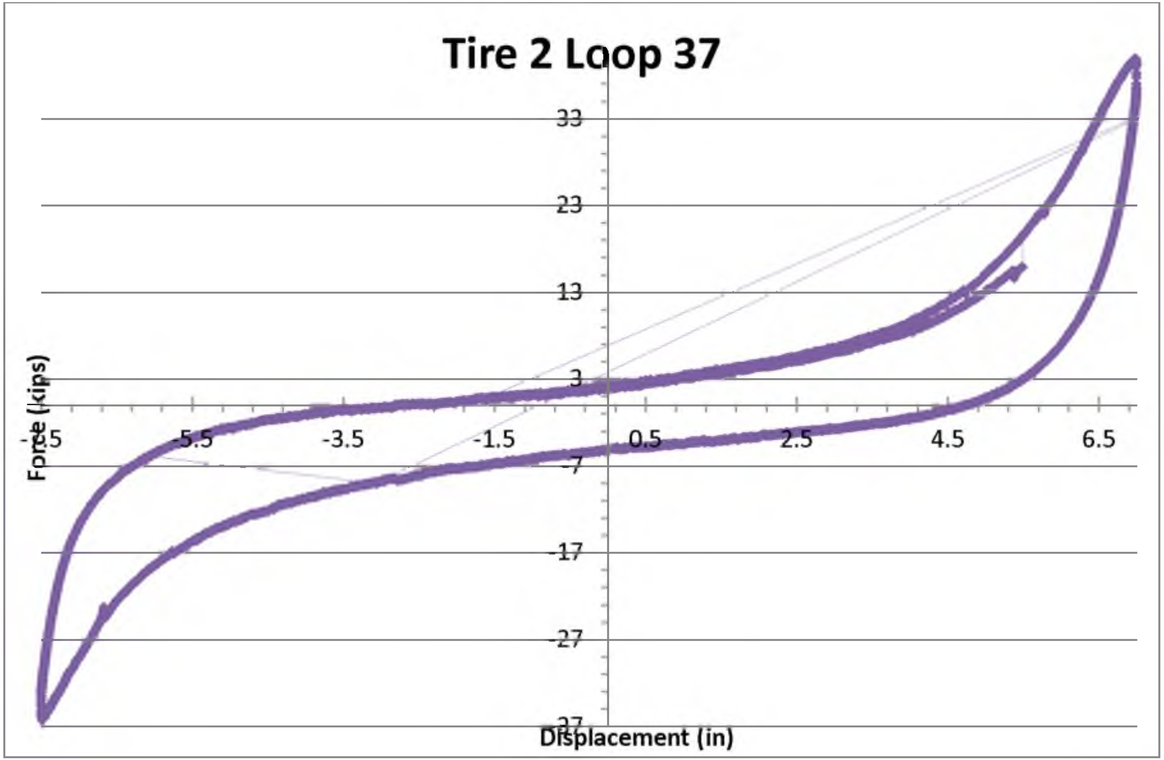

Tire 2 Loop 33
30
20
10
0
-10
-20
-30
-5.5
-3.5
-1.5
0.5
2.5
4.5
Force (kips)
Displacement (in)


Tire 2 Loop 34
30
20
10
0
-10
-20
-30
-6
-4
-2
0
2
4
6
Force (kips)
Displacement (in)

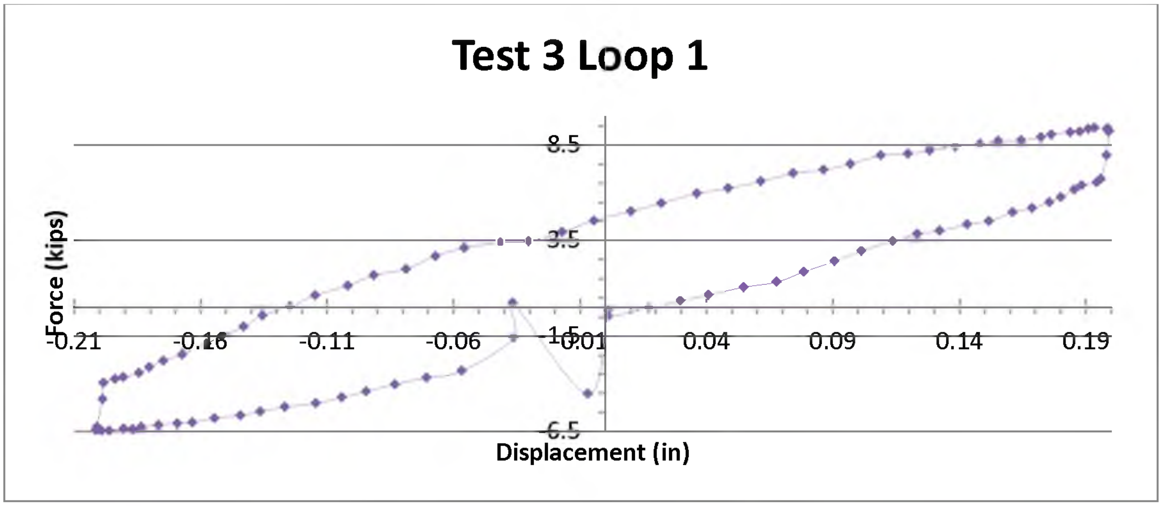

Tire 2 Loop 35
27
17
7
-3
-13
-23
-4.5
-2.5
-0.5
1.5
3.5
5.5
Force (kips)
Displacement (in)

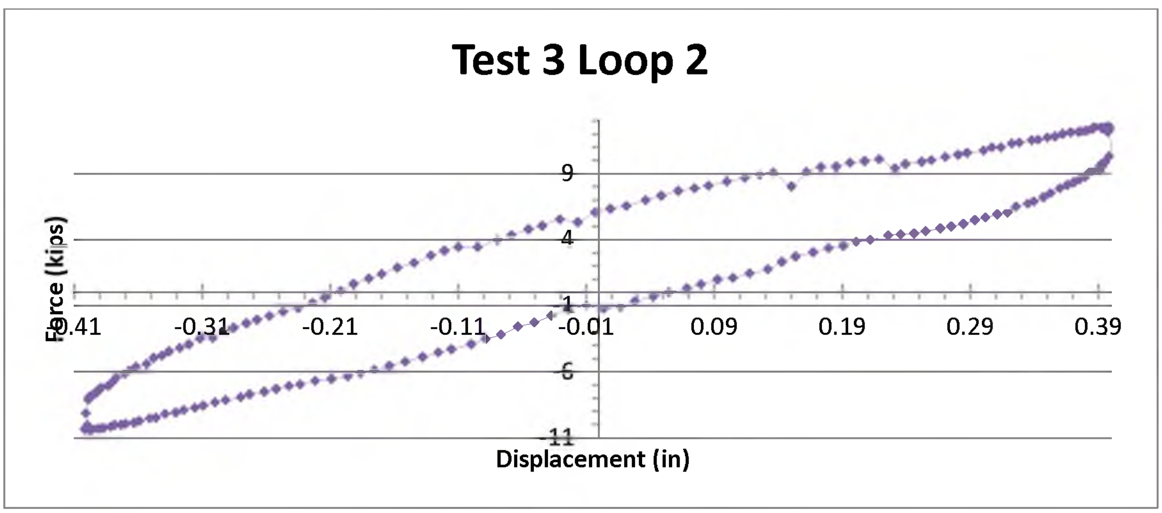

Tire 2 Loop 36
37
27
17
7
-3
-13
-23
-3
-1
1
3
5
Force (kips)
Displacement (in)

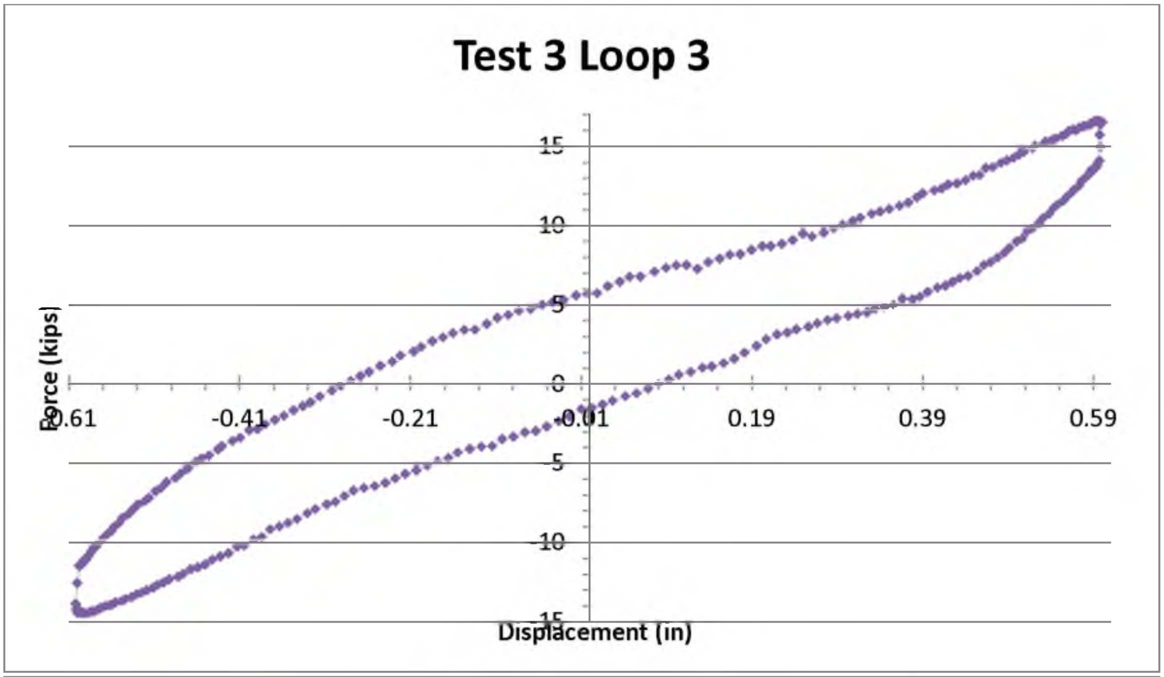

Tire 2 Loop 38
40
30
20
10
0
-10
-20
-30
-40
-7.6
-5.6
-3.6
-1.6
0.4
2.4
4.4
6.4
Force (kips)
Displacement (in)

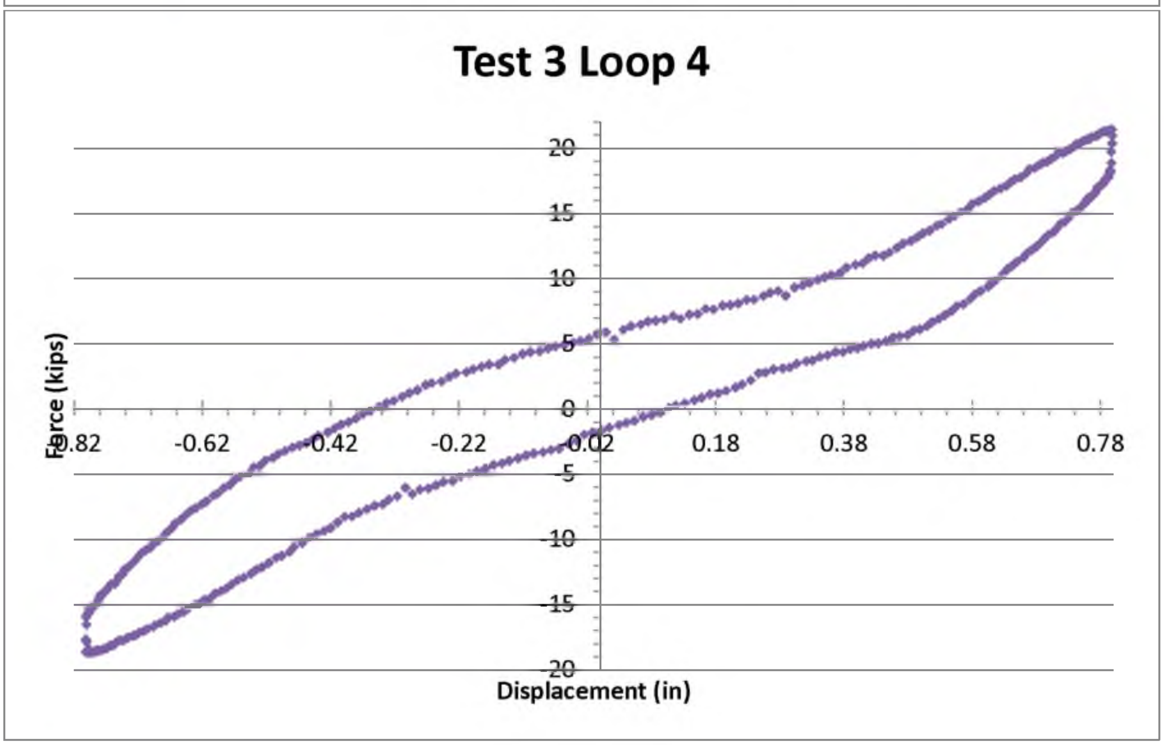

Tire 2 Loop 37
33
23
13
3
-7
-17
-27
-37
-7.5
-5.5
-3.5
-1.5
0.5
2.5
4.5
6.5
Force (kips)
Displacement (in)

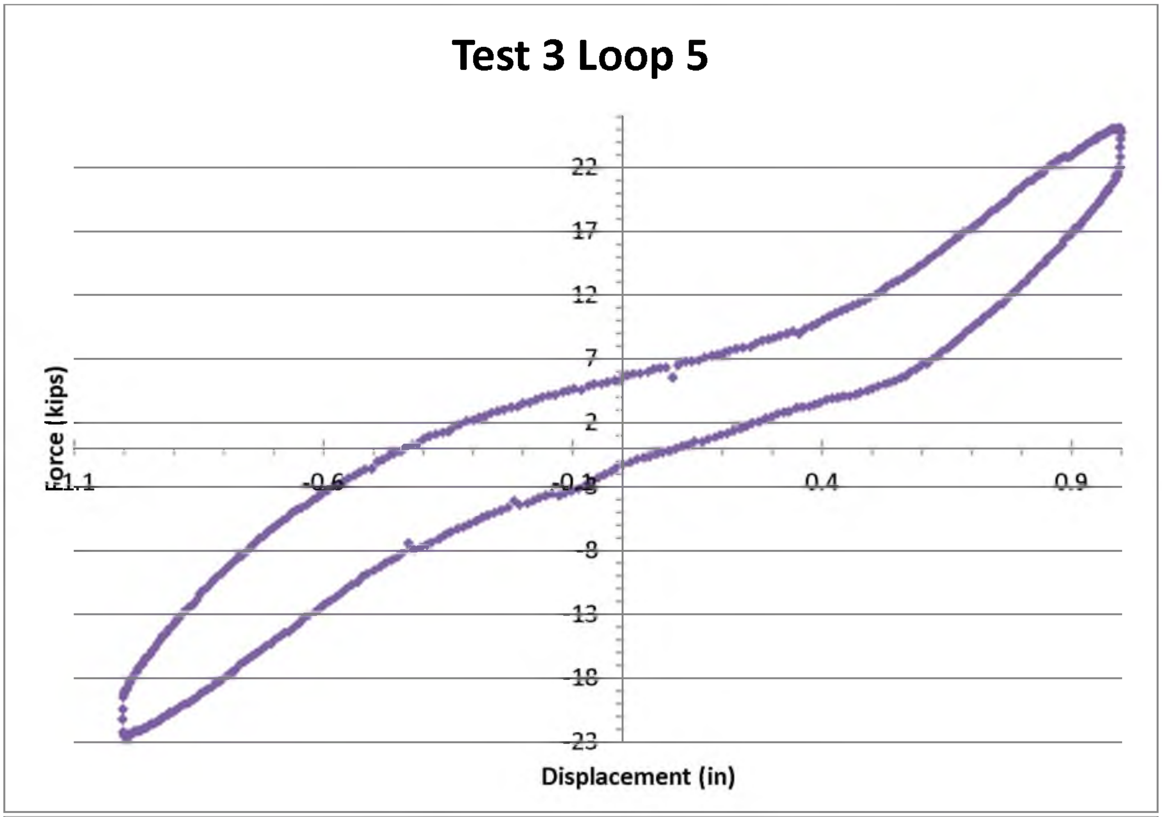
Test Three Individual Loops – 32 Total

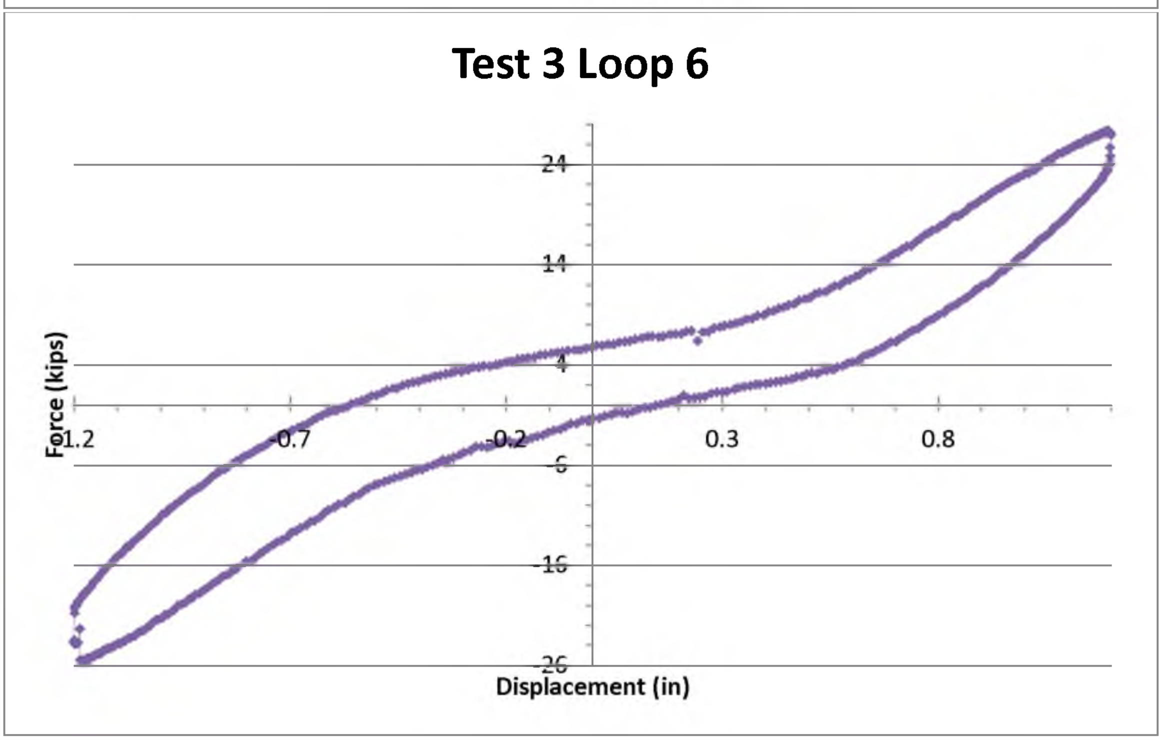


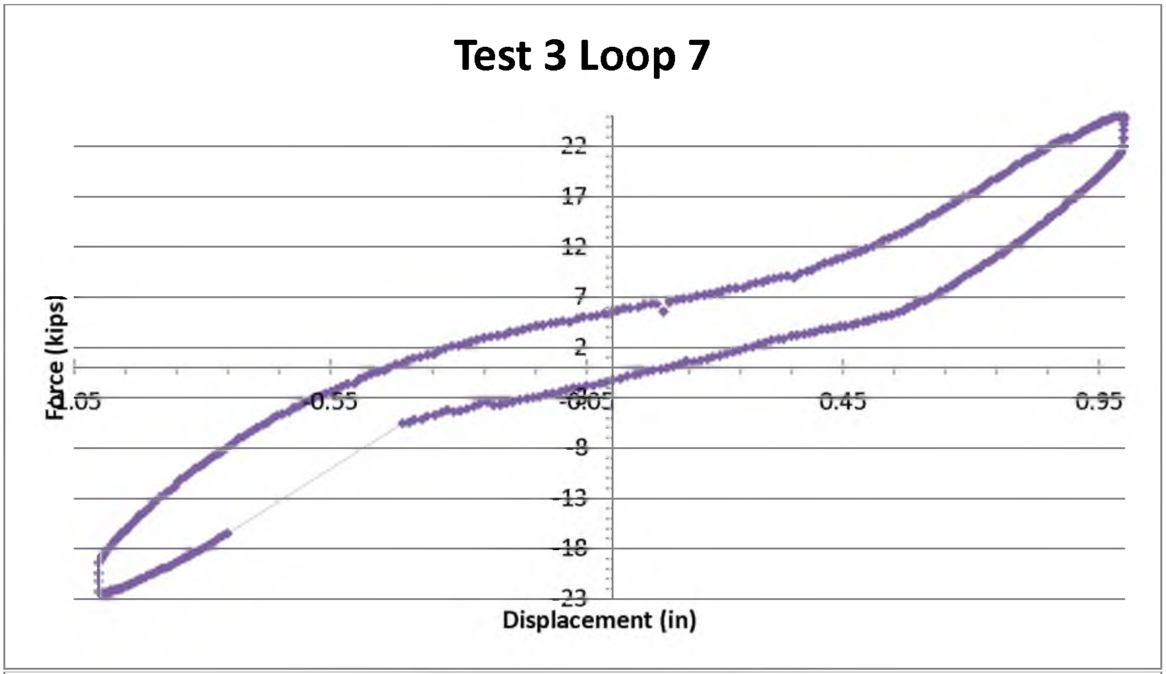



Test 3 Loop 3
Force (kips)
Displacement (in)
15
10
5
0
-5
-10
-15
-0.61
-0.41
-0.21
-0.01
0.19
0.39
0.59

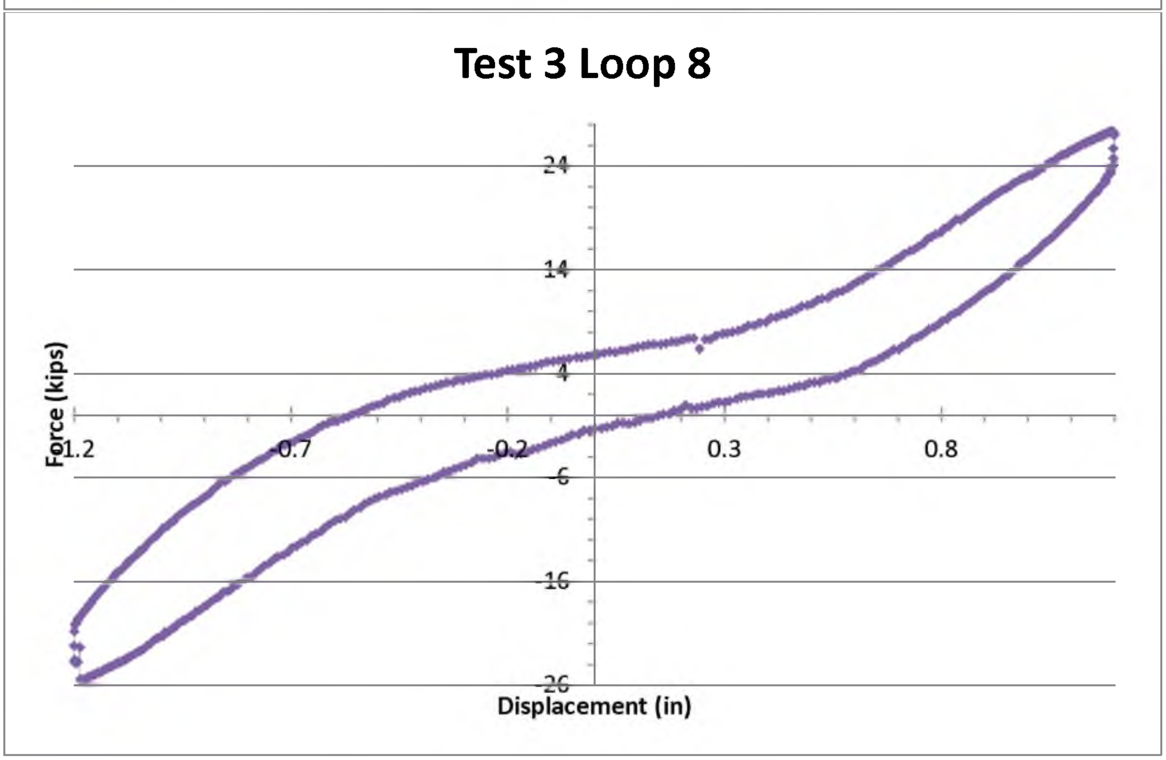

Test 3 Loop 4
Force (kips)
Displacement (in)
20
15
10
5
0
-5
-10
-15
-20
-0.82
-0.62
-0.42
-0.22
-0.02
0.18
0.38
0.58
0.78


Test 3 Loop 5
22
17
12
7
2
-1.1
-0.6
-0.1
-3
0.4
0.9
-8
-13
-18
-23
Force (kips)
Displacement (in)

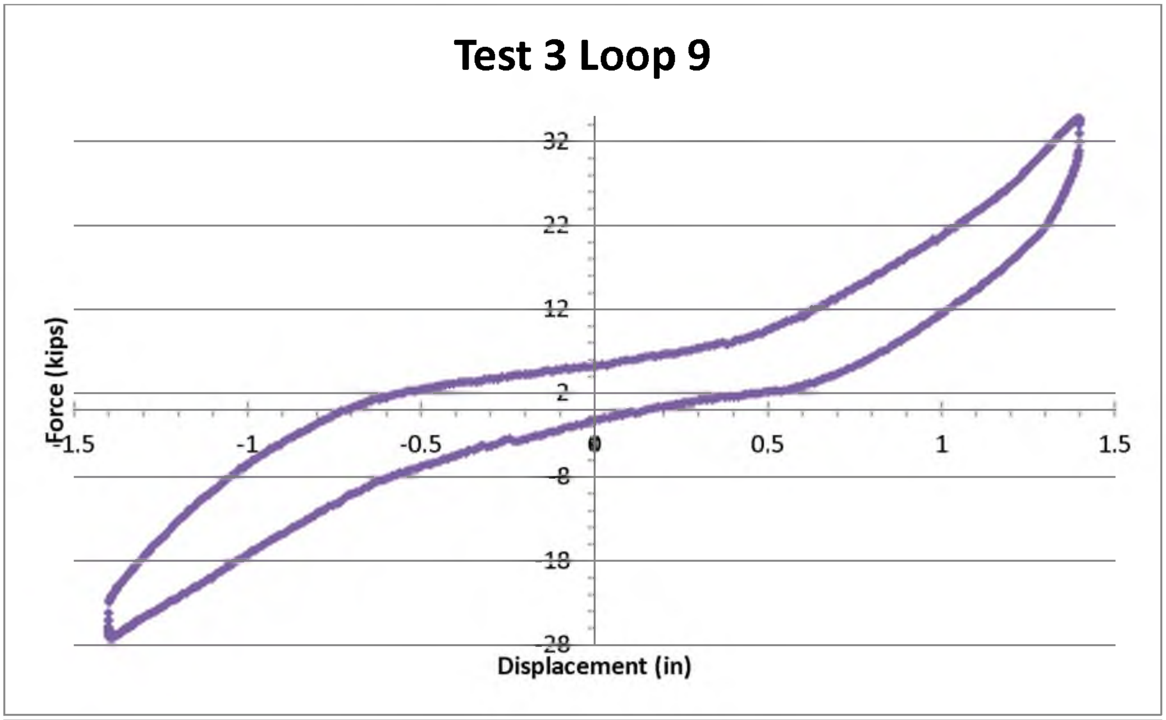

Test 3 Loop 6
24
14
4
-1.2
-0.7
-0.2
0.3
0.8
-6
-16
-26
Force (kips)
Displacement (in)

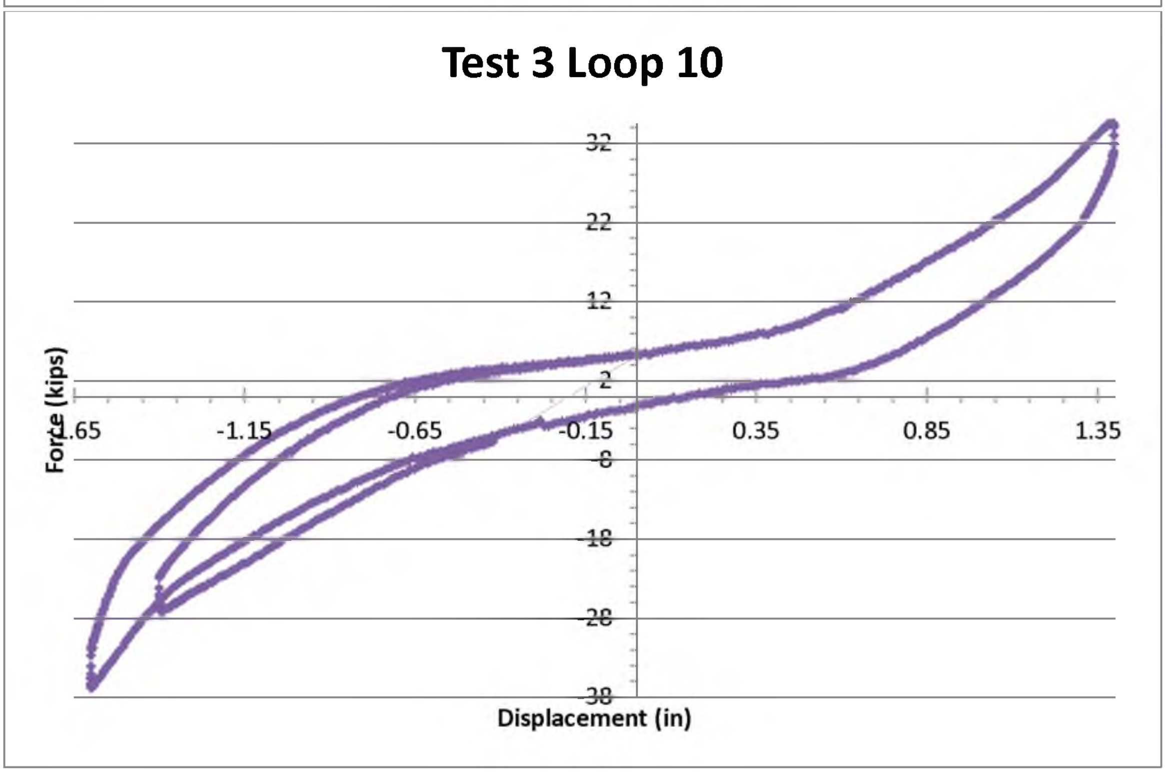


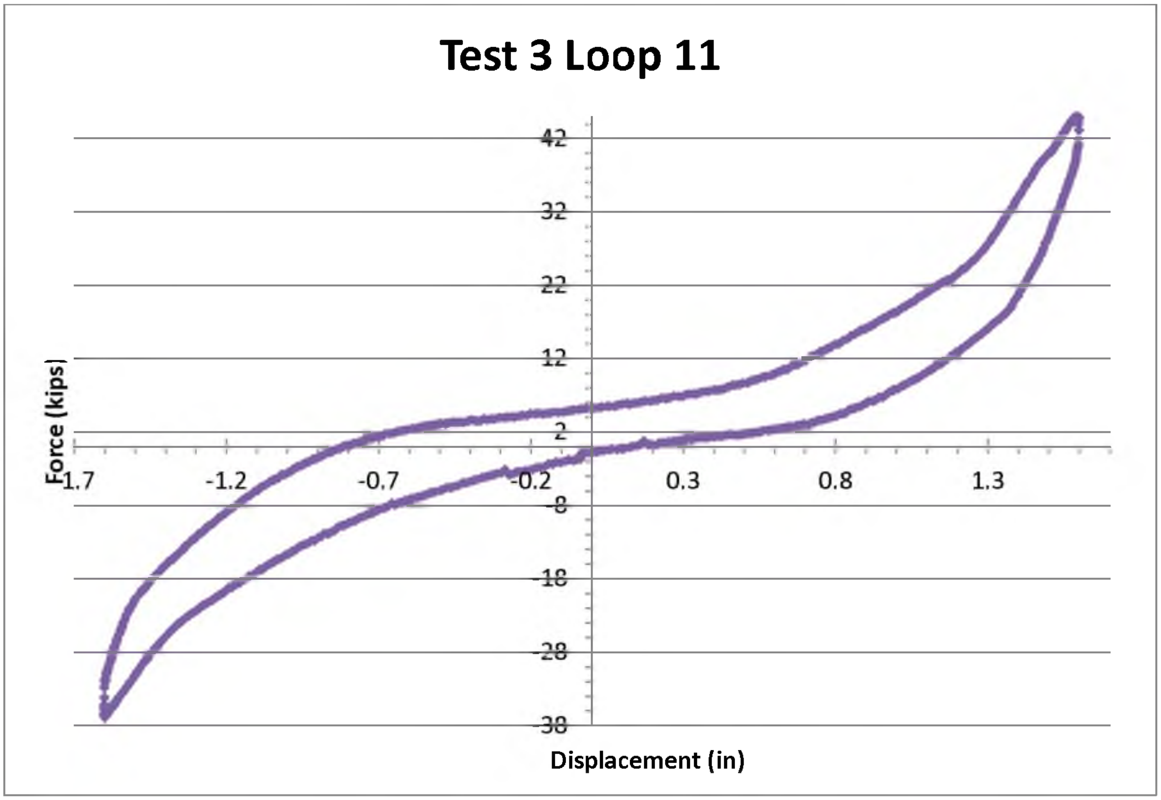
Test 3 Loop 7
Force (kips)
Displacement (in)
22
17
12
7
2
-3
-8
-13
-18
-23
-1.05
-0.55
-0.05
0.45
0.95

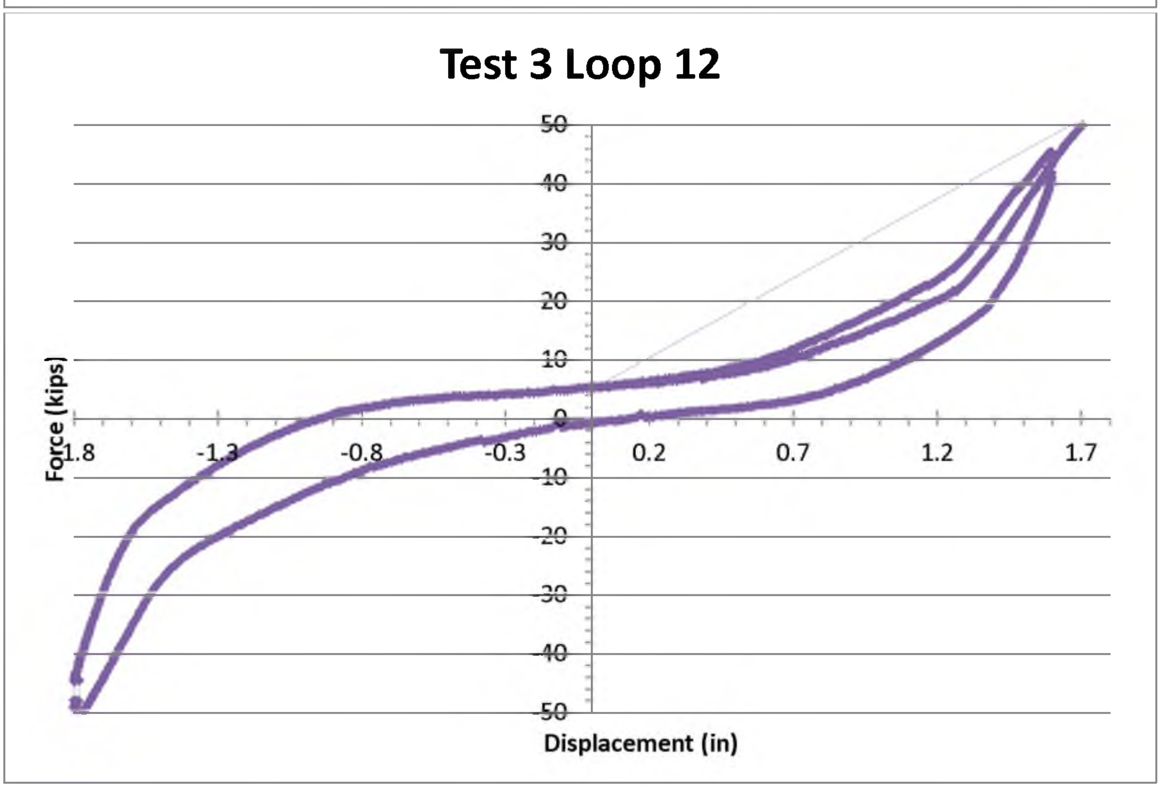


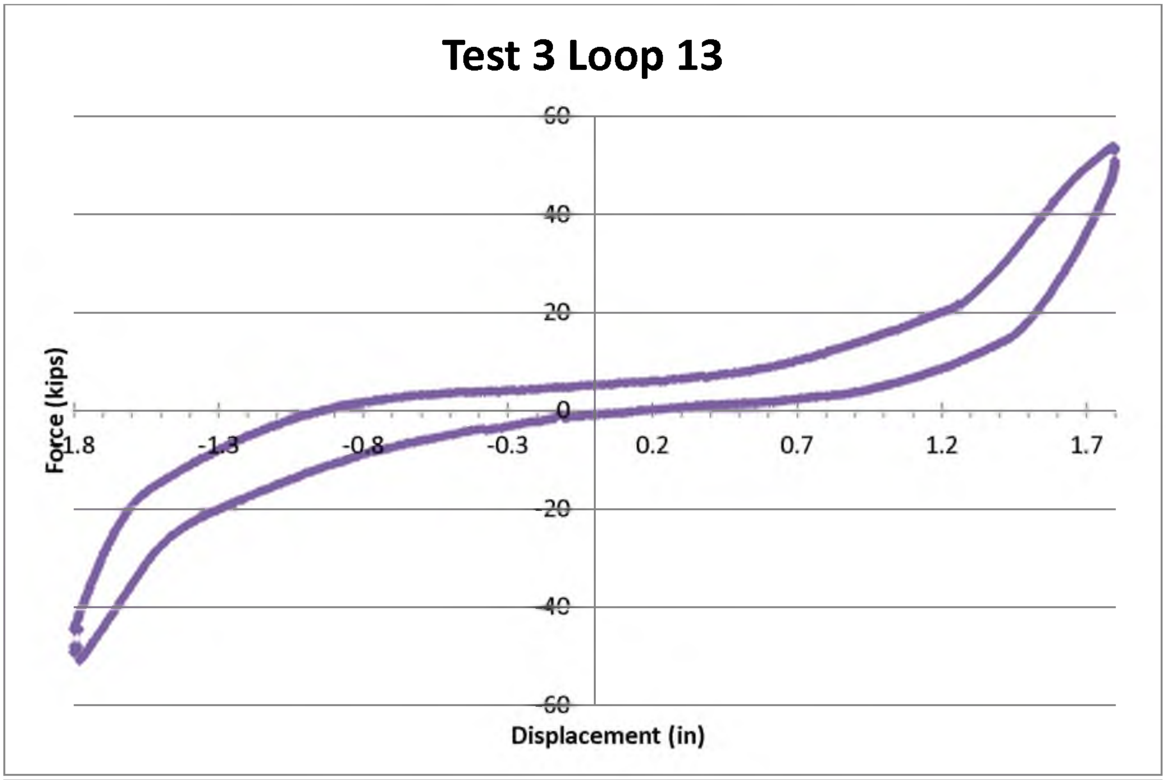
Test 3 Loop 8
Force (kips)
Displacement (in)
24
14
4
-6
-16
-26
-1.2
-0.7
-0.2
0.3
0.8

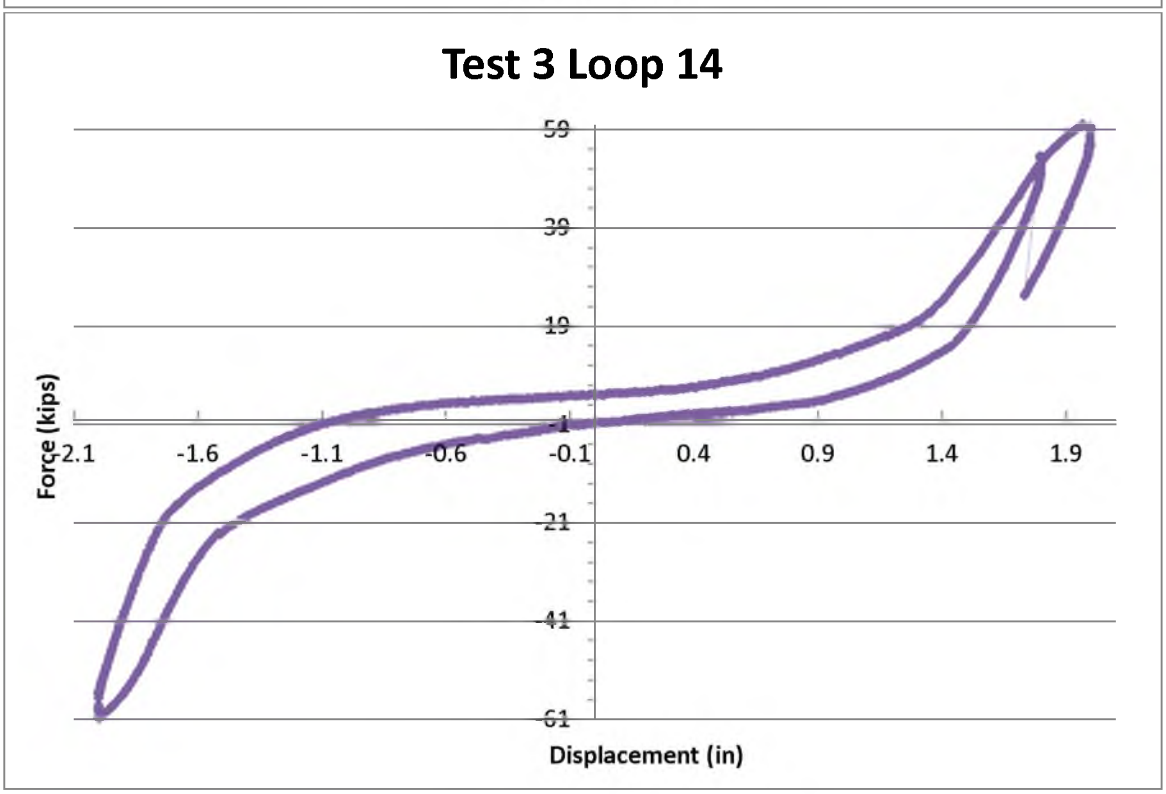

Test 3 Loop 9
32
22
12
2
-8
-18
-28
-1.5
-1
-0.5
0
0.5
1
1.5
Force (kips)
Displacement (in)

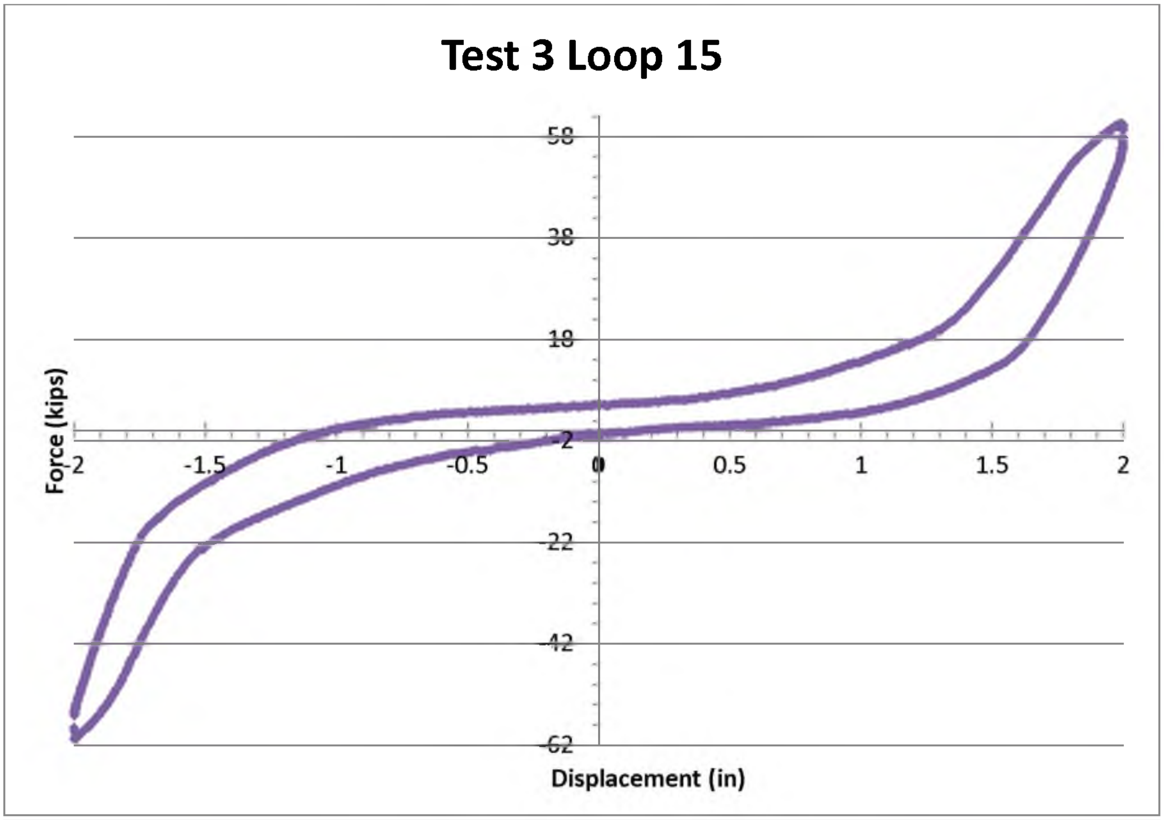

Test 3 Loop 10
32
22
12
2
-8
-18
-28
-38
-1.65
-1.15
-0.65
-0.15
0.35
0.85
1.35
Force (kips)
Displacement (in)

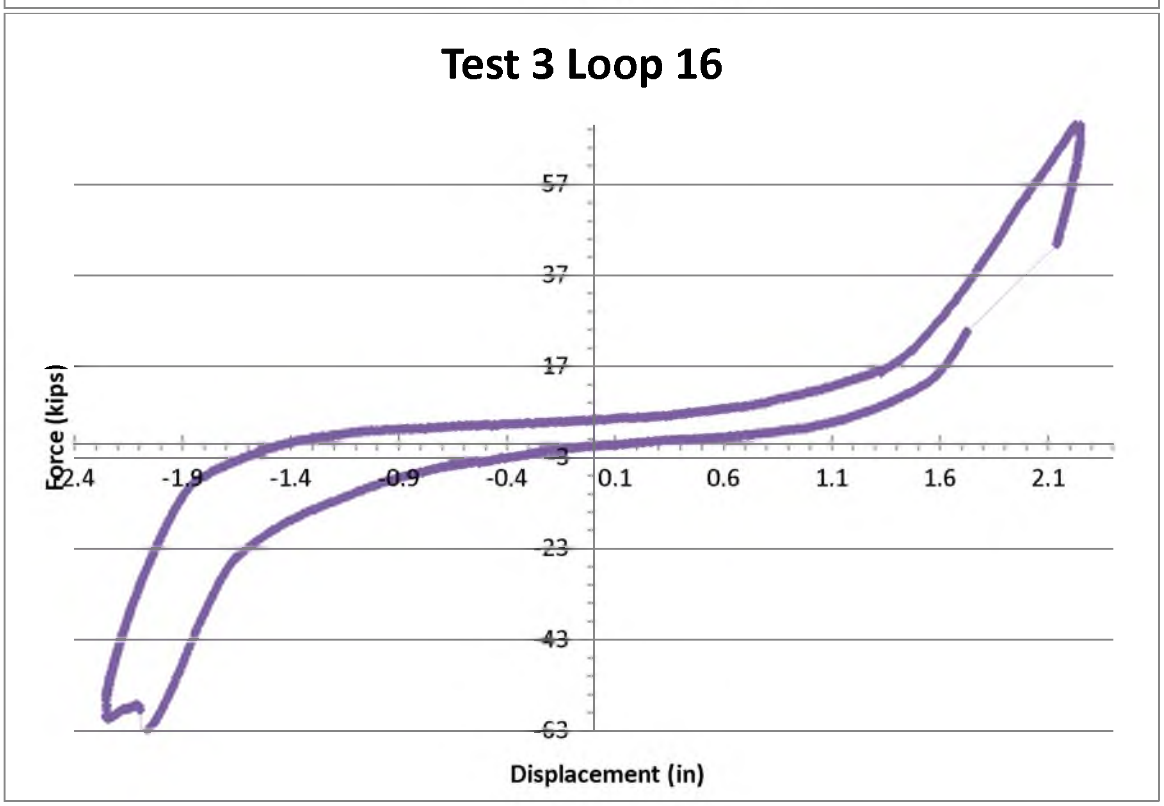

Test 3 Loop 11
42
32
22
12
2
-8
-18
-28
-38
Force (kips)
-1.7
-1.2
-0.7
-0.2
0.3
0.8
1.3
Displacement (in)

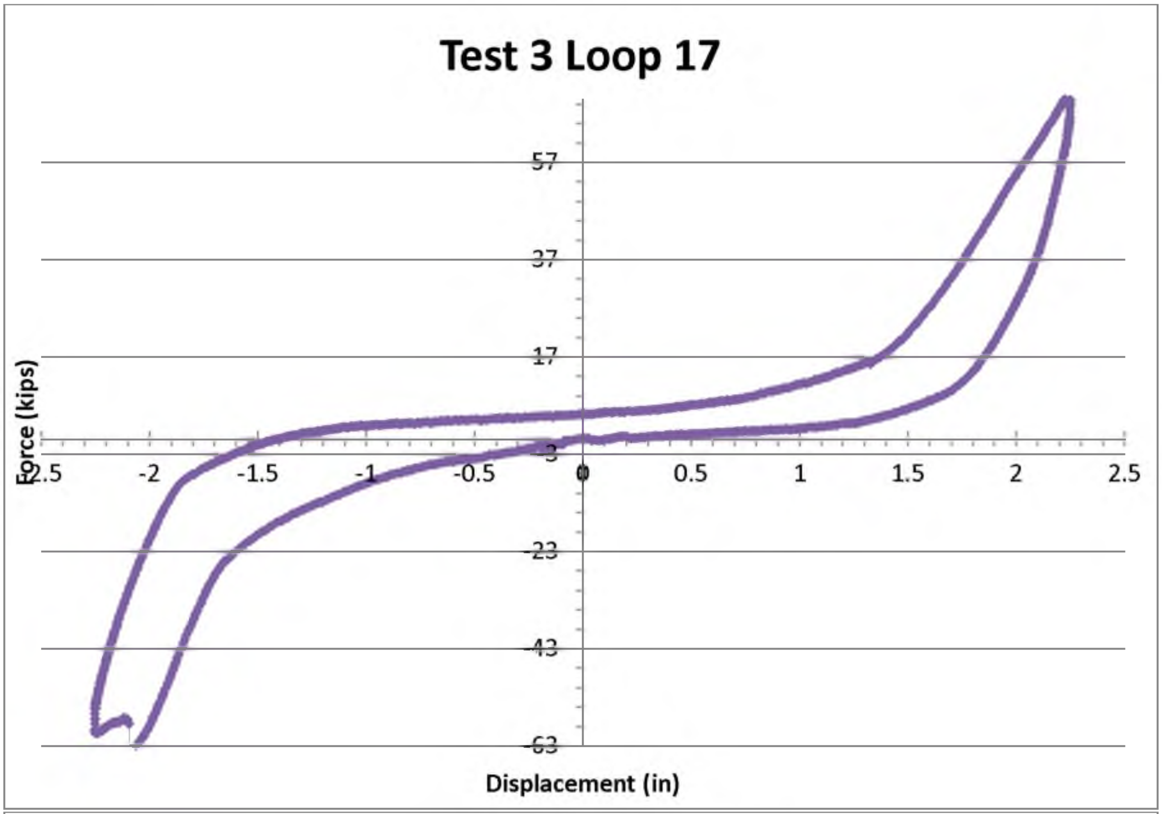

Test 3 Loop 12
50
40
30
20
10
0
-10
-20
-30
-40
-50
Force (kips)
-1.8
-1.3
-0.8
-0.3
0.2
0.7
1.2
1.7
Displacement (in)

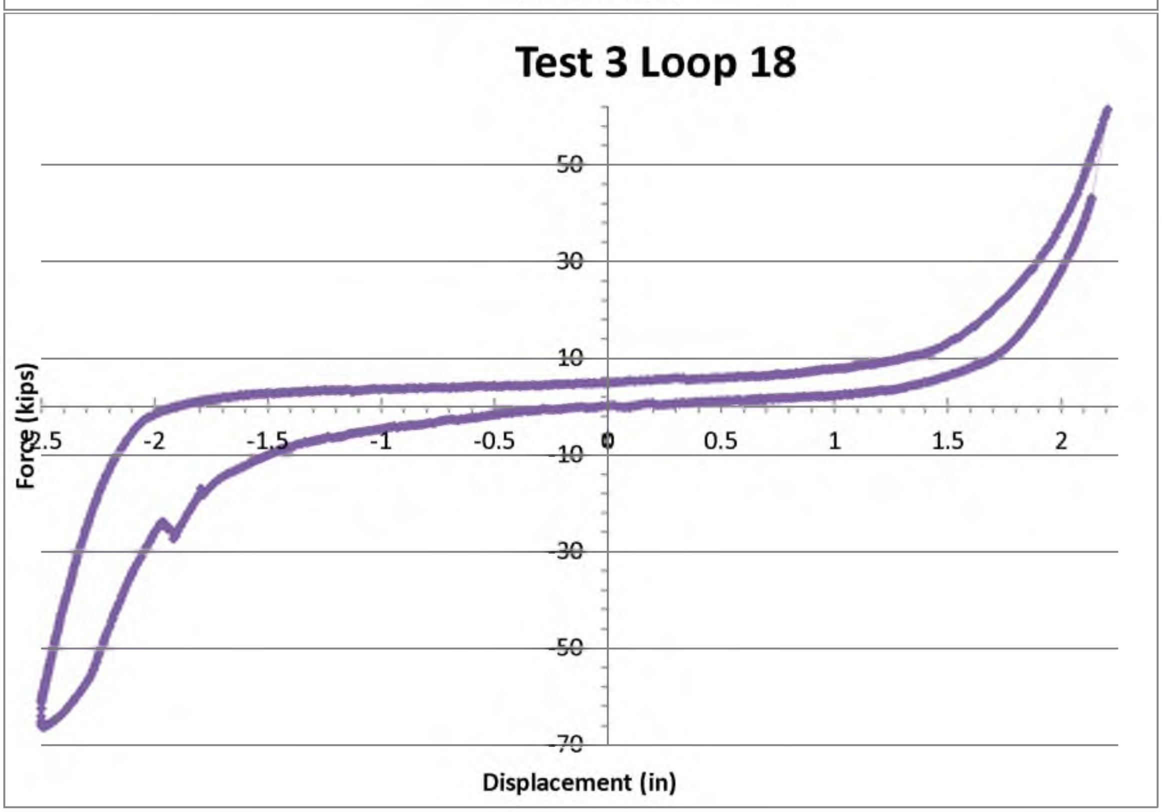

Test 3 Loop 13
60
40
20
0
-20
-40
-60
-1.8
-1.3
-0.8
-0.3
0.2
0.7
1.2
1.7
Force (kips)
Displacement (in)

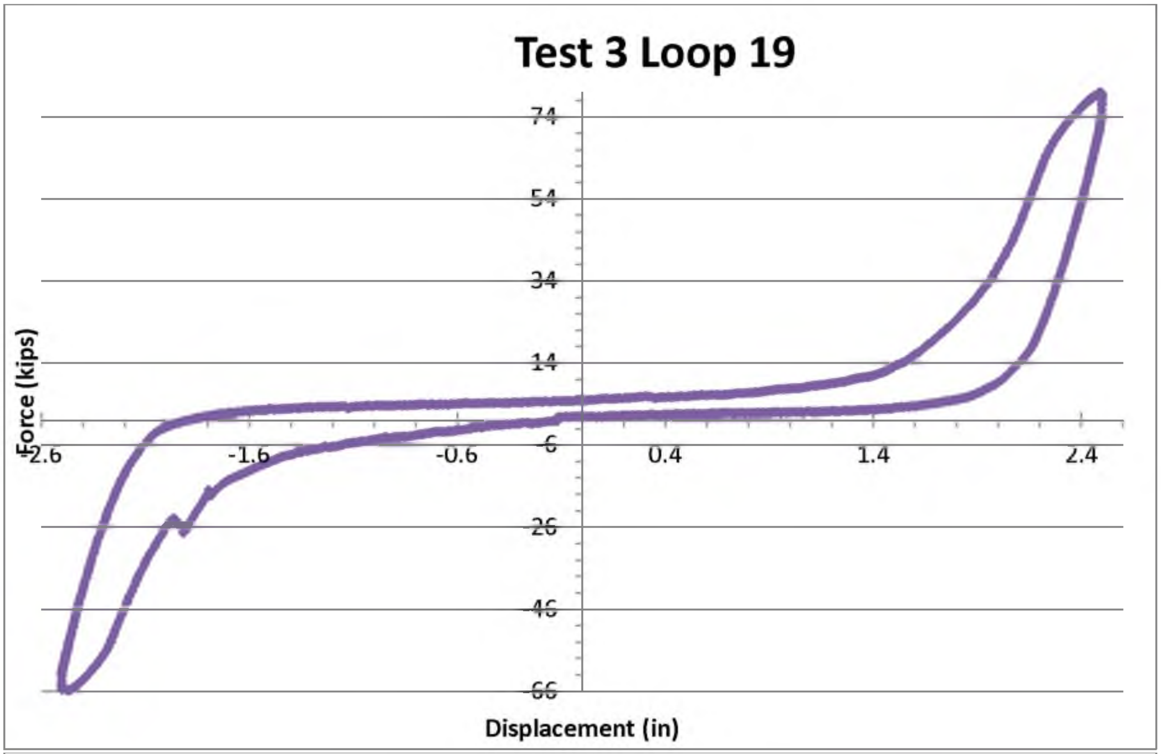

Test 3 Loop 14
59
39
19
-1
-21
-41
-61
-2.1
-1.6
-1.1
-0.6
-0.1
0.4
0.9
1.4
1.9
Force (kips)
Displacement (in)

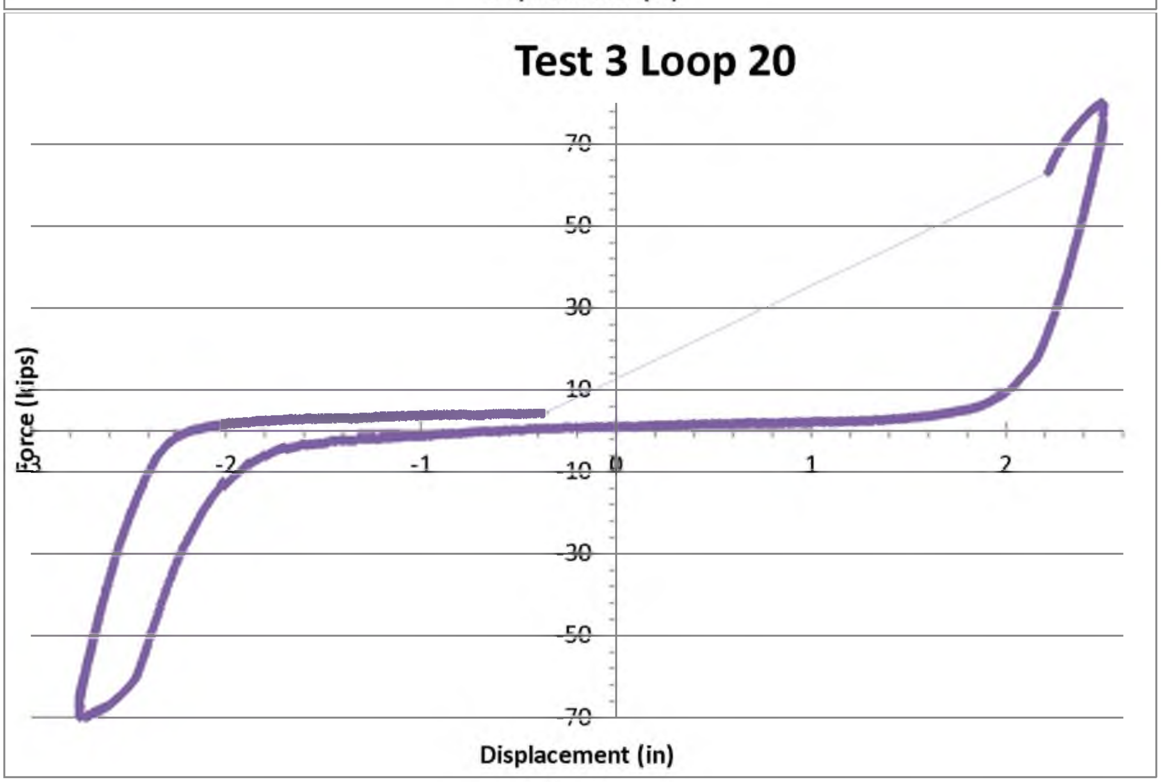

Test 3 Loop 15
58
38
18
-2
-22
-42
-62
Force (kips)
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Displacement (in)

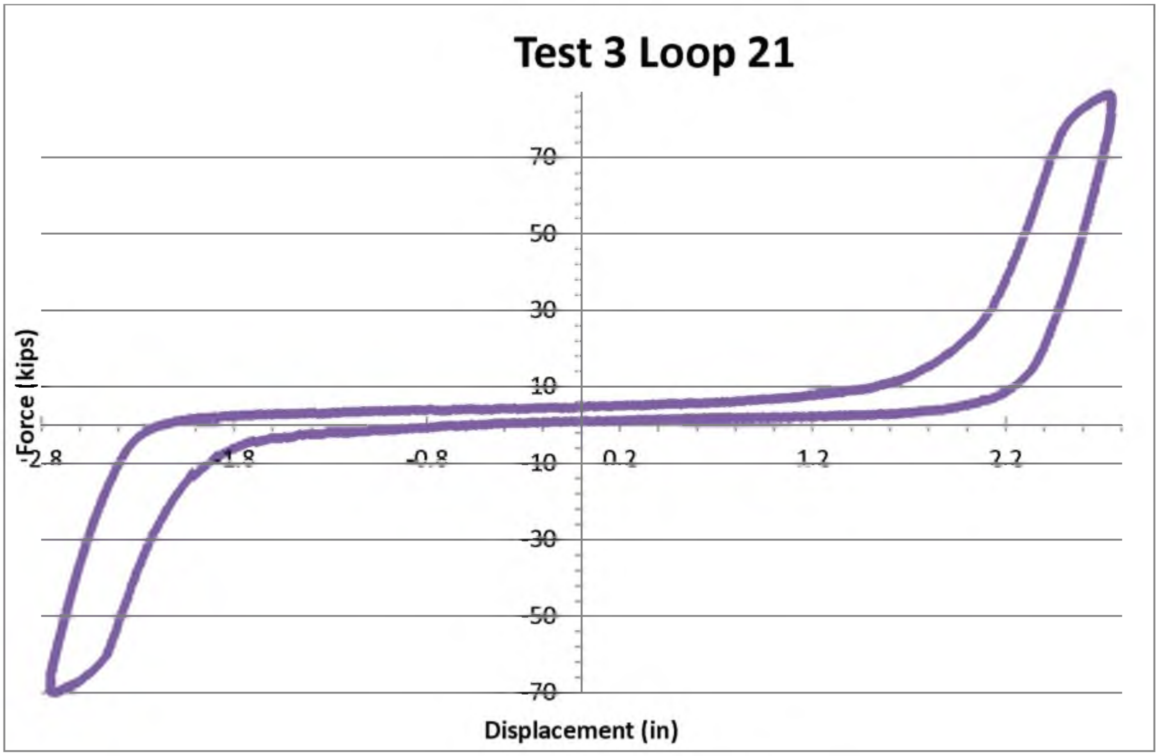

Test 3 Loop 16
57
37
17
-3
-23
-43
-63
Force (kips)
-2.4
-1.9
-1.4
-0.9
-0.4
0.1
0.6
1.1
1.6
2.1
Displacement (in)

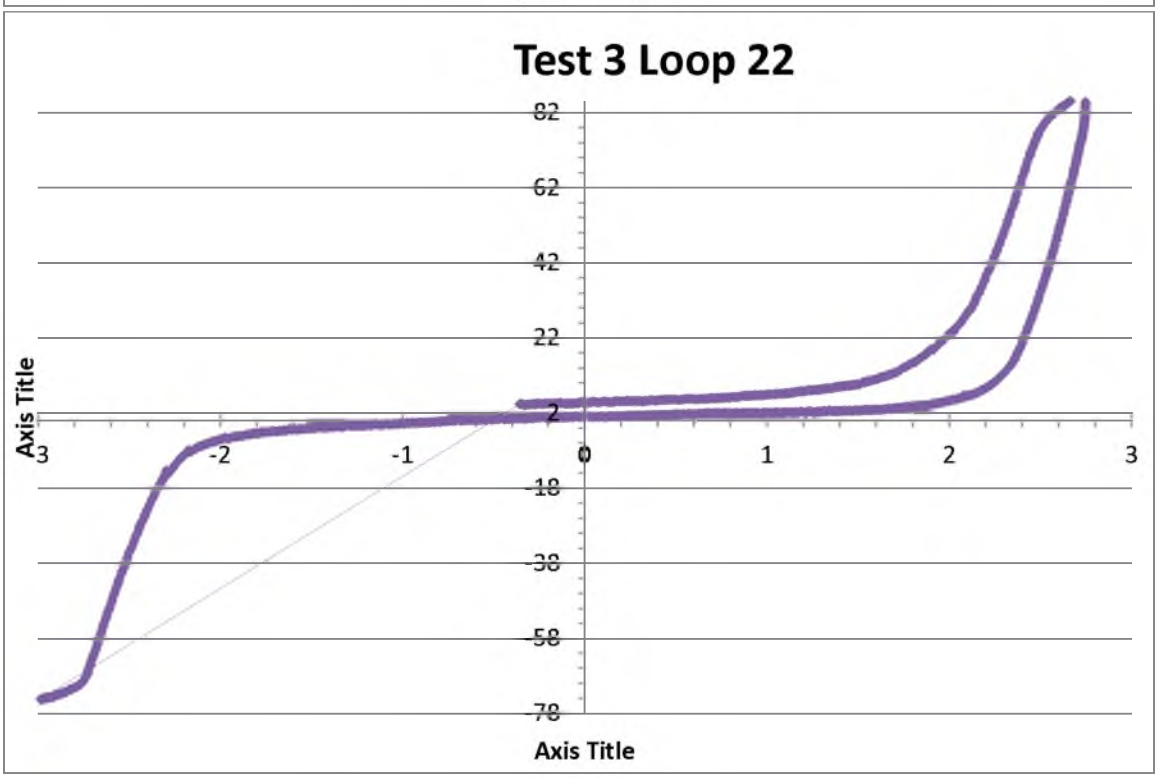

Test 3 Loop 17
57
37
17
-3
-23
-43
-63
Force (kips)
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
2.5
Displacement (in)

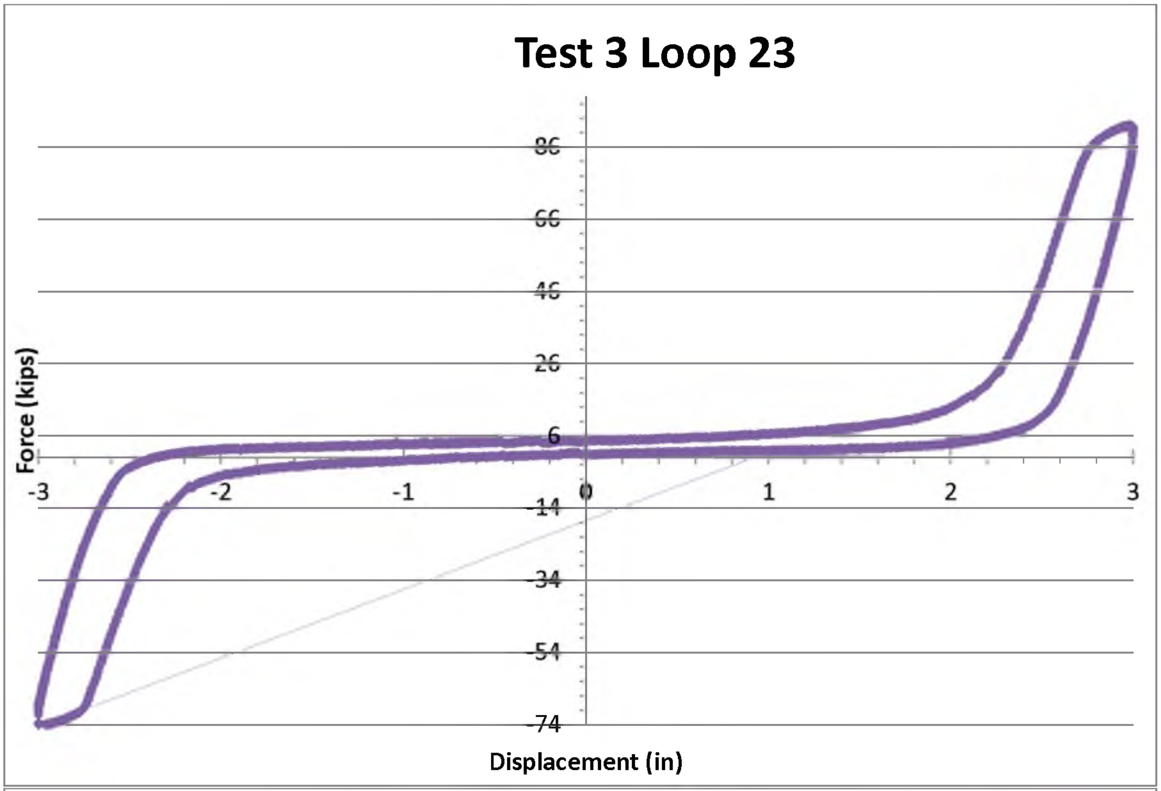

Test 3 Loop 18
50
30
10
-10
-30
-50
-70
Force (kips)
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
Displacement (in)

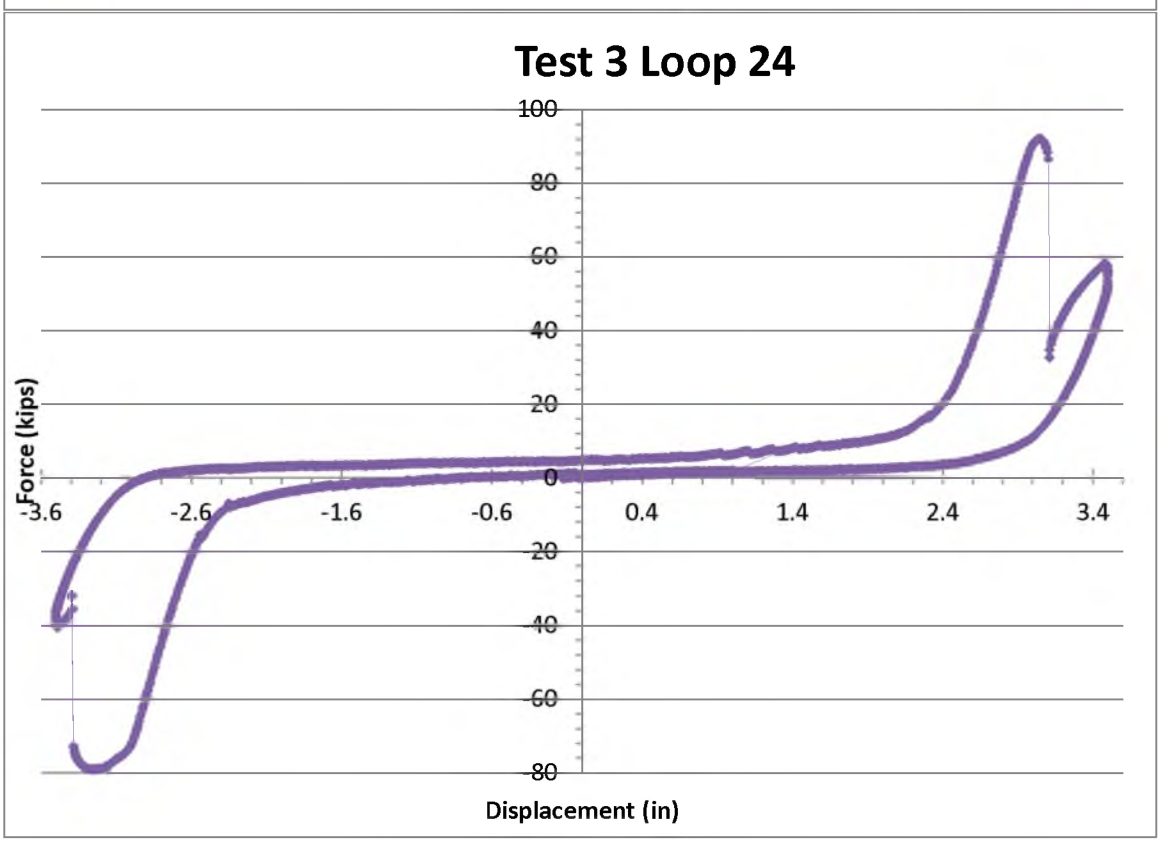

Test 3 Loop 19
74
54
34
14
-6
-26
-46
-66
-2.6
-1.6
-0.6
0.4
1.4
2.4
Force (kips)
Displacement (in)

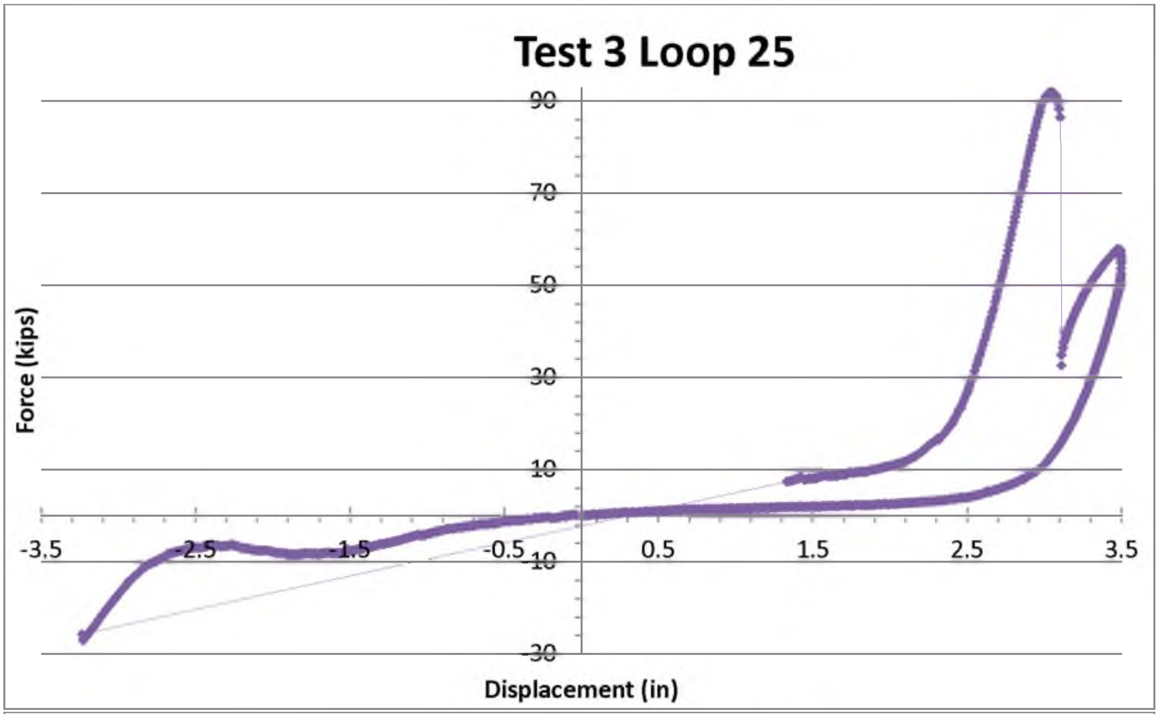

Test 3 Loop 20
70
50
30
10
-10
-30
-50
-70
-3
-2
-1
0
1
2
Force (kips)
Displacement (in)

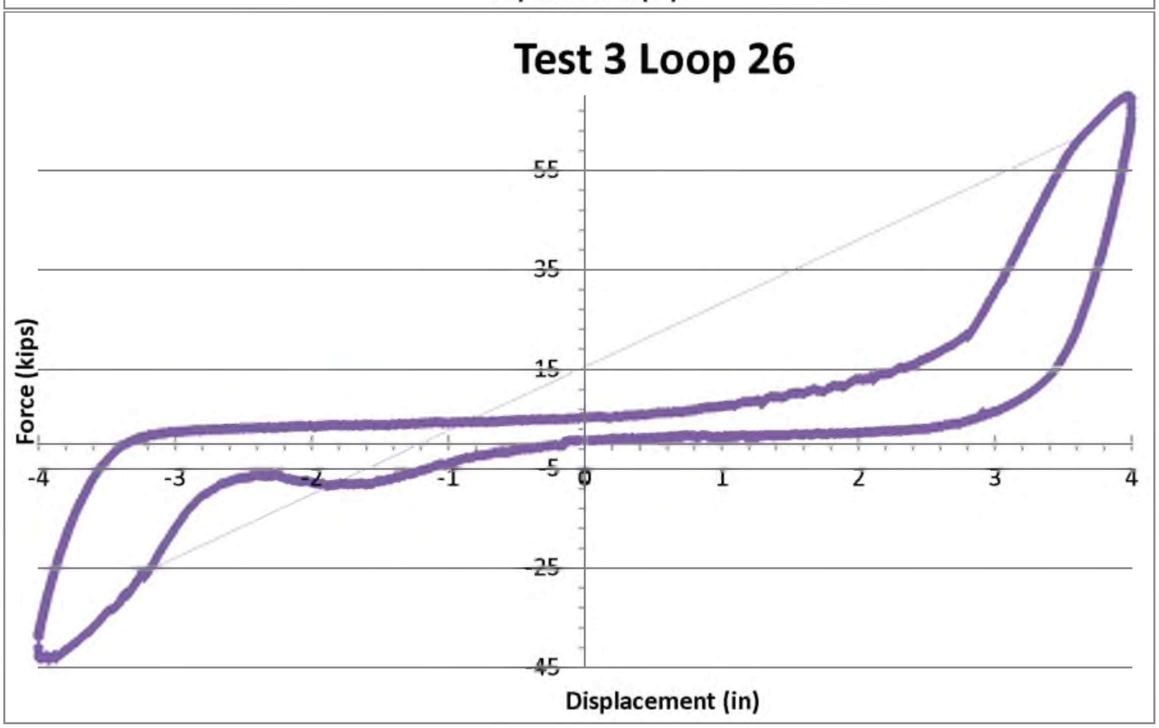

Test 3 Loop 21
Force (kips)
Displacement (in)
70
50
30
10
-10
-30
-50
-70
-2.8
-1.8
-0.8
0.2
1.2
2.2

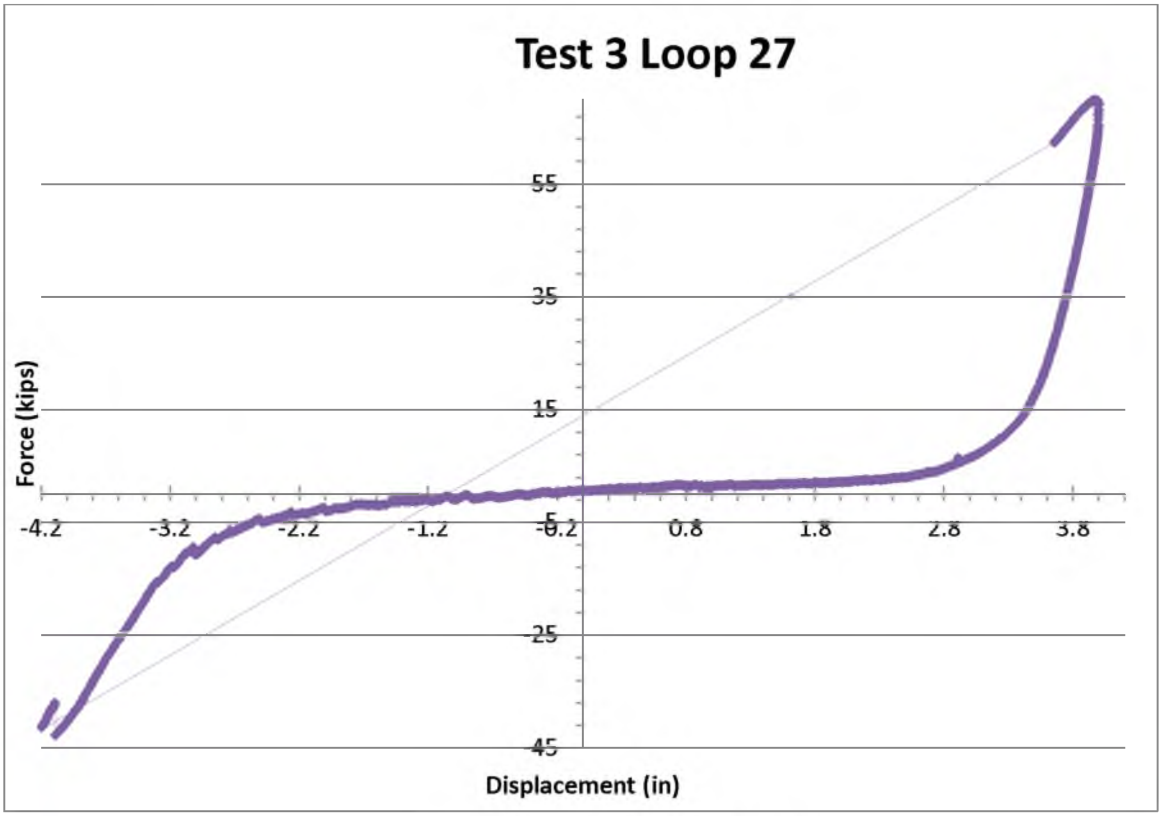

Test 3 Loop 22
Axis Title
Axis Title
82
62
42
22
2
-18
-38
-58
-78
-3
-2
-1
0
1
2
3


Test 3 Loop 23
Force (kips)
86
66
46
26
6
-14
-34
-54
-74
-3
-2
-1
0
1
2
3
Displacement (in)

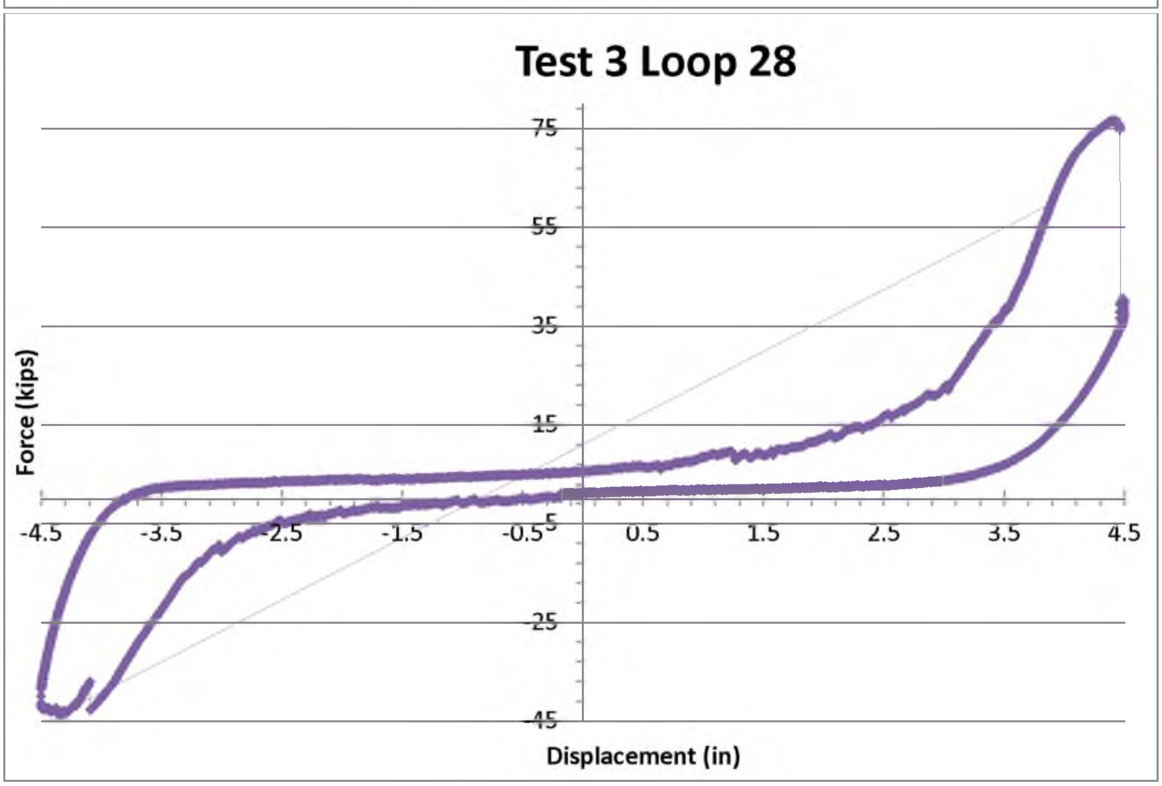

Test 3 Loop 24
Force (kips)
100
80
60
40
20
0
-20
-40
-60
-80
-3.6
-2.6
-1.6
-0.6
0.4
1.4
2.4
3.4
Displacement (in)


Test 3 Loop 25
Force (kips)
90
70
50
30
10
-10
-30
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
3.5
Displacement (in)

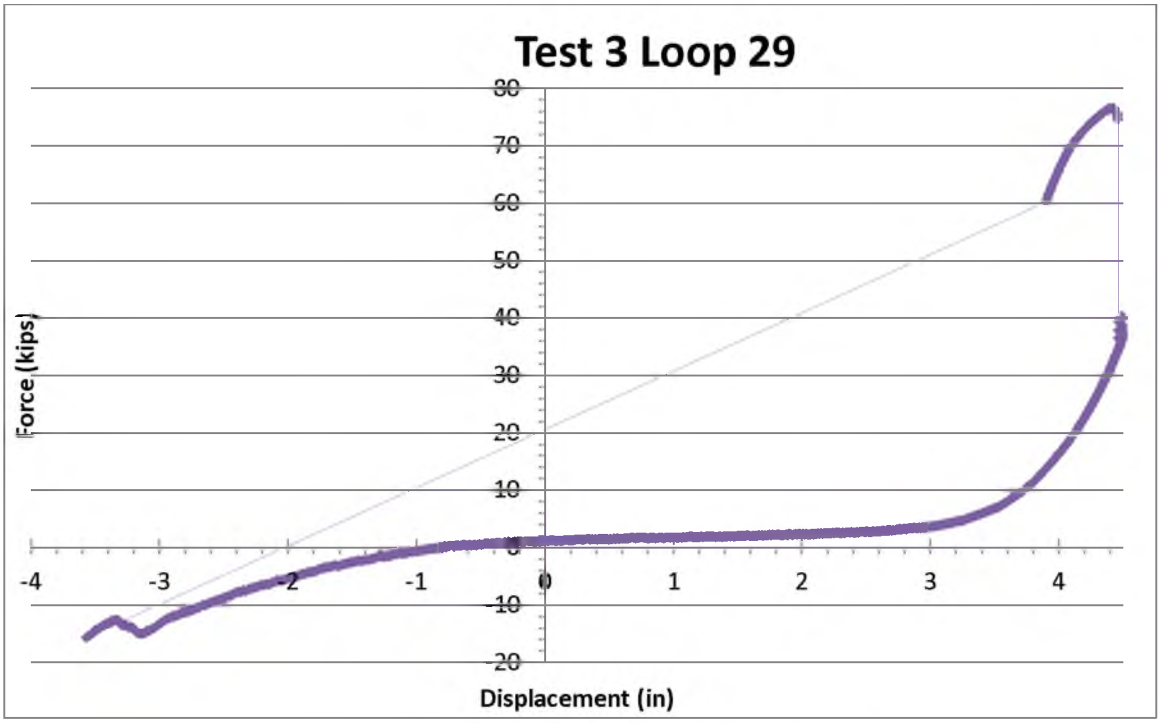

Test 3 Loop 26
Force (kips)
55
35
15
-5
-25
-45
-4
-3
-2
-1
0
1
2
3
4
Displacement (in)

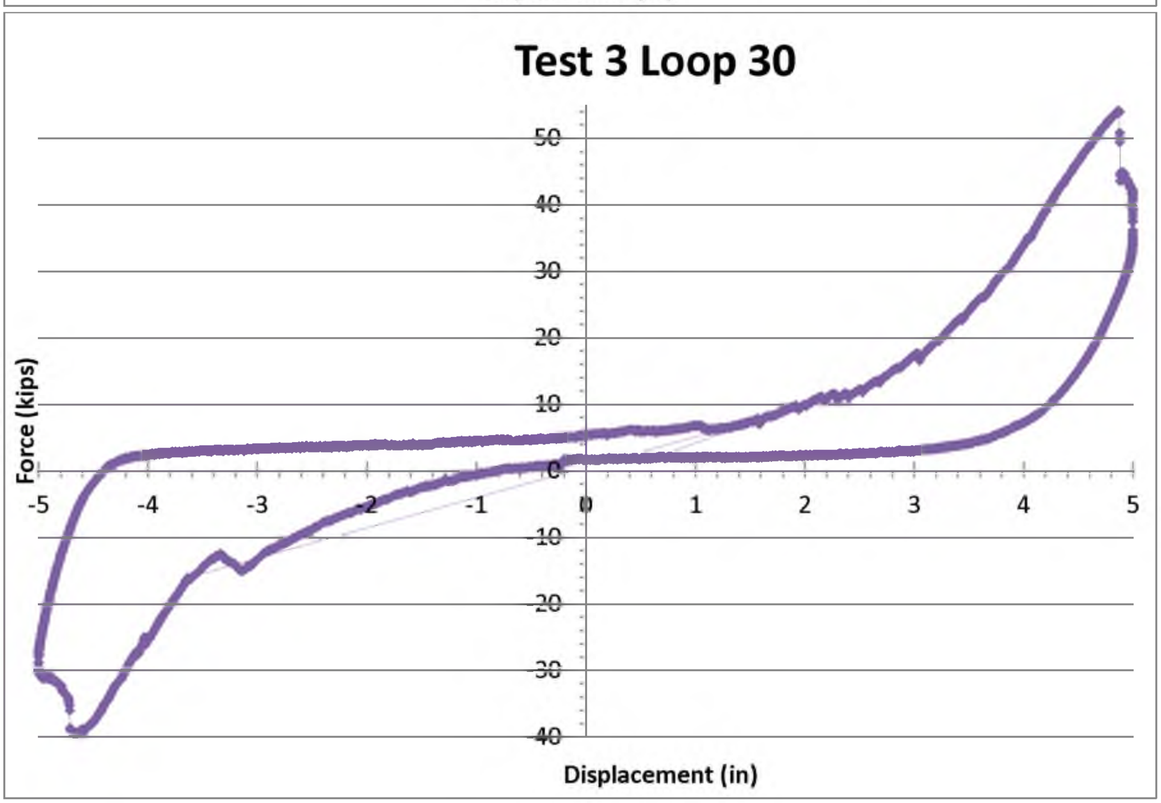


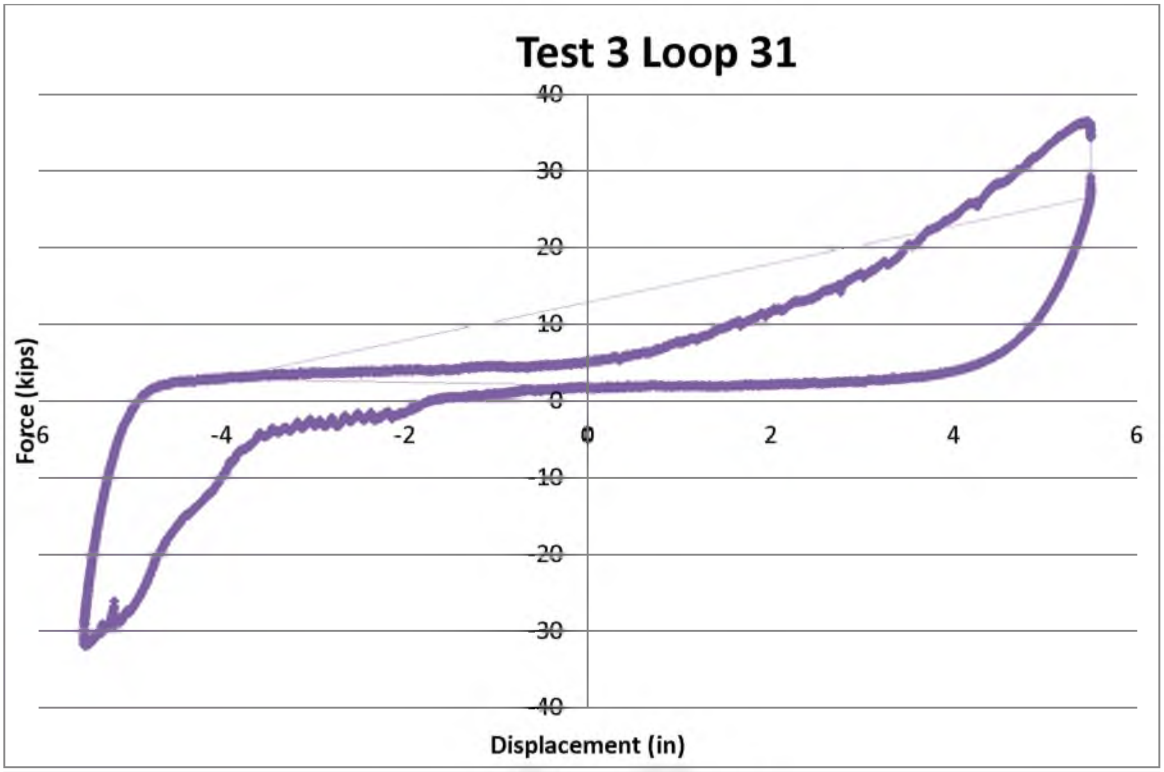
Test 3 Loop 27
55
35
15
-5
-25
-45
-4.2
-3.2
-2.2
-1.2
-0.2
0.8
1.8
2.8
3.8
Force (kips)
Displacement (in)

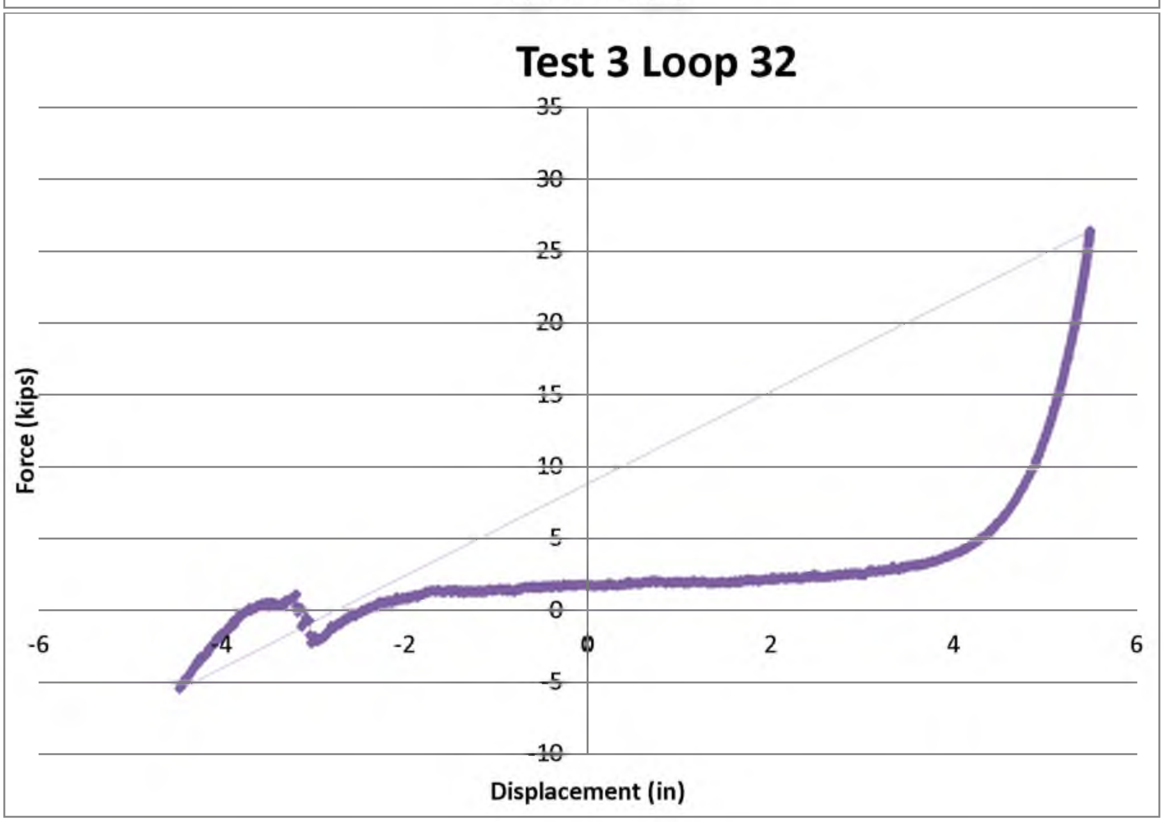


Test 3 Loop 28
75
55
35
15
-5
-25
-45
-4.5
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
3.5
4.5
Force (kips)
Displacement (in)

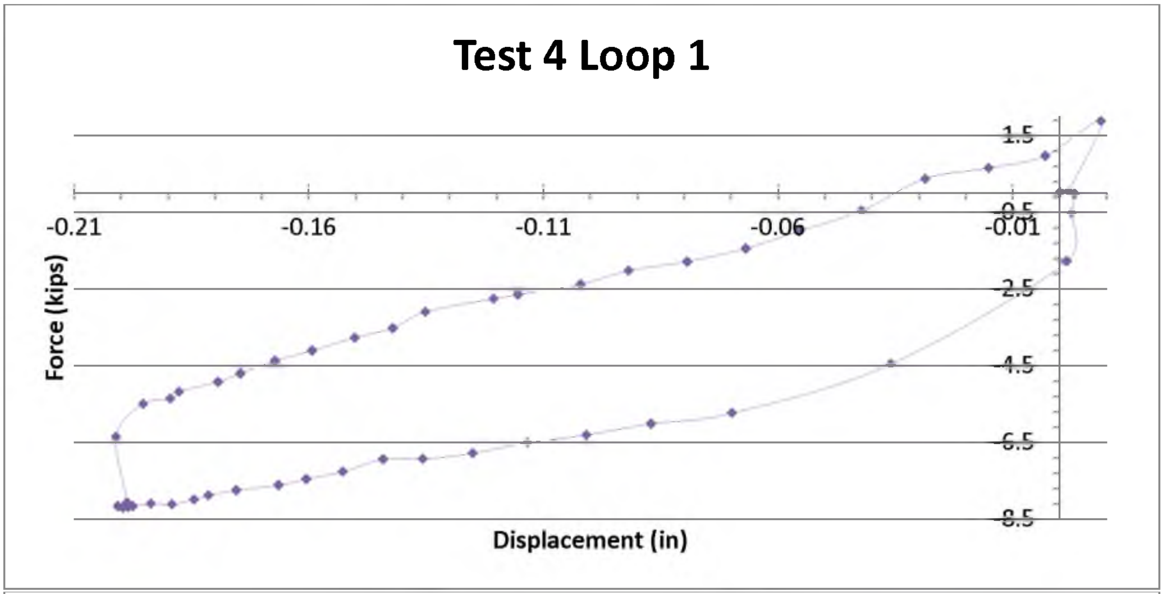

Test 3 Loop 29
80
70
60
50
40
30
20
10
0
-10
-20
-4
-3
-2
-1
0
1
2
3
4
Force (kips)
Displacement (in)

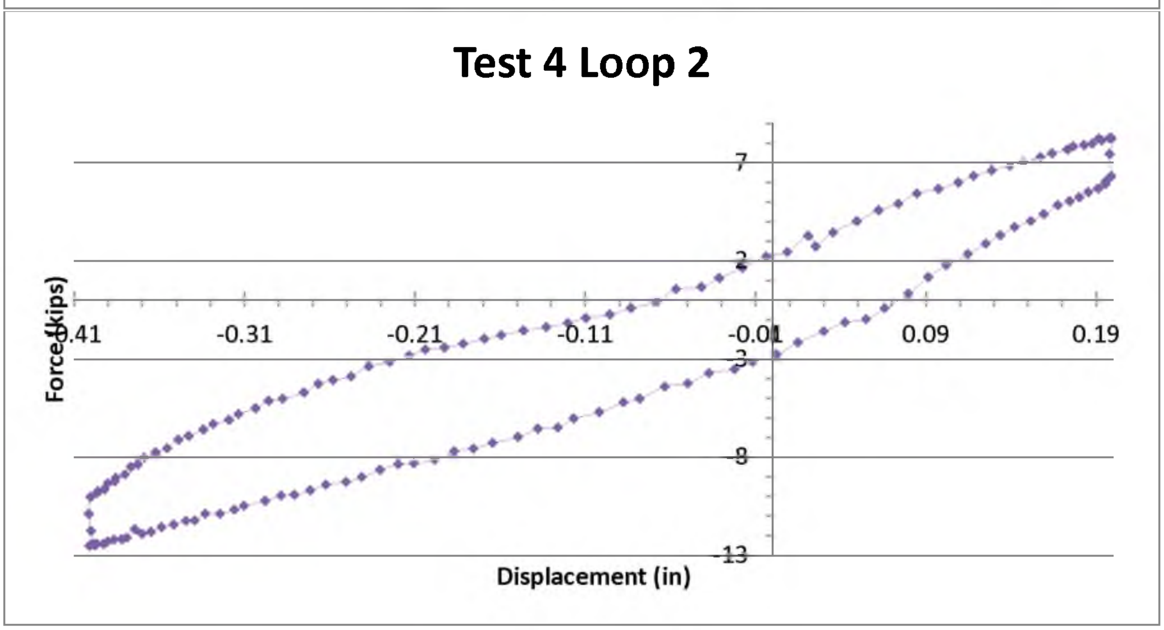

Test 3 Loop 30
50
40
30
20
10
0
-10
-20
-30
-40
-5
-4
-3
-2
-1
0
1
2
3
4
5
Force (kips)
Displacement (in)

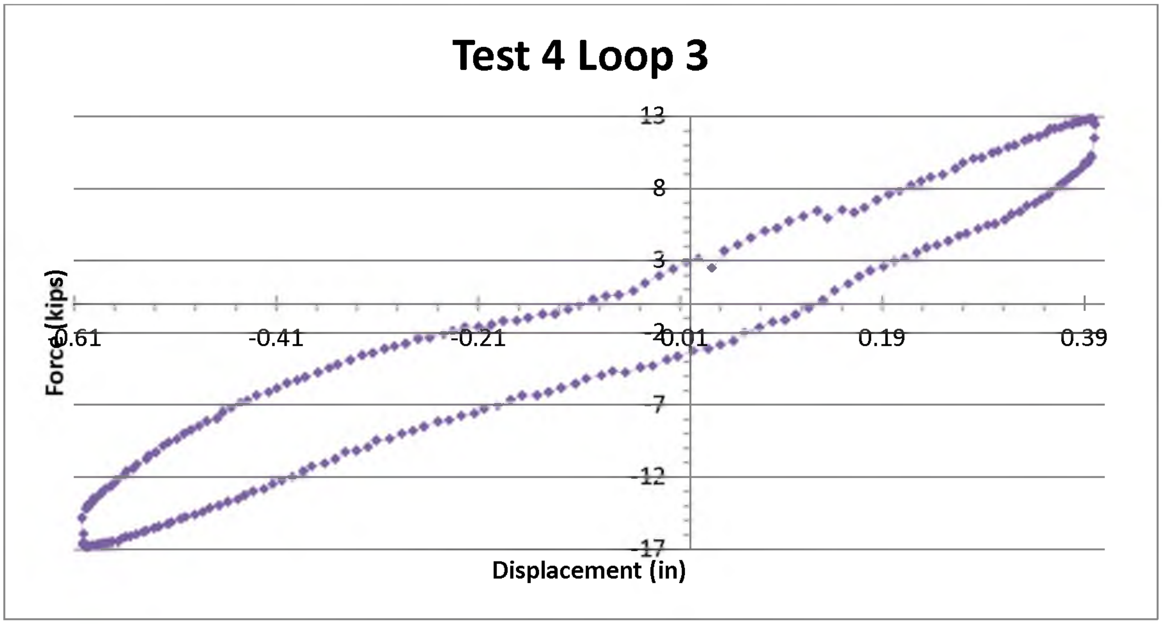

Test 3 Loop 31
40
30
20
10
0
-10
-20
-30
-40
-6
-4
-2
0
2
4
6
Force (kips)
Displacement (in)

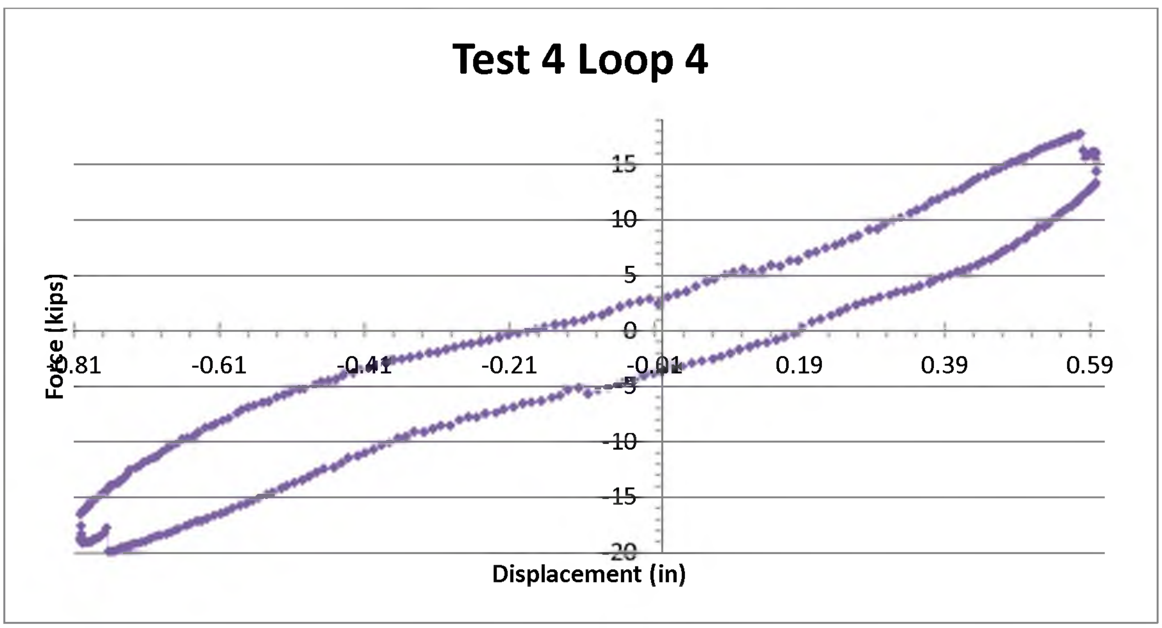

Test 3 Loop 32
35
30
25
20
15
10
5
0
-5
-10
-6
-4
-2
0
2
4
6
Force (kips)
Displacement (in)

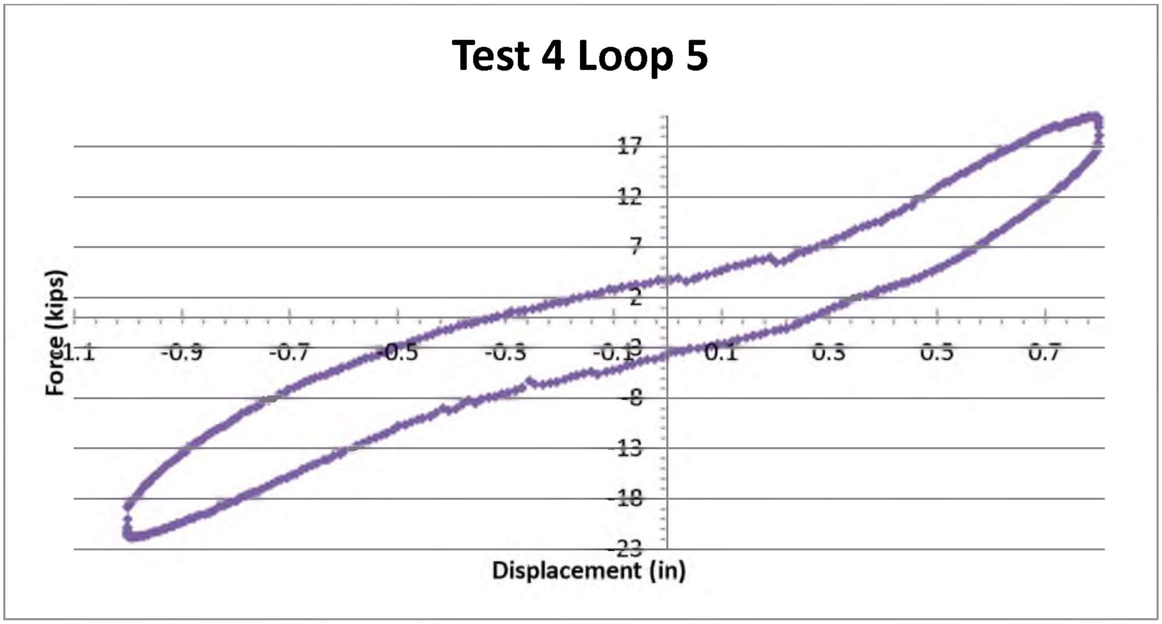
Test Four Individual Loops – 35 Total

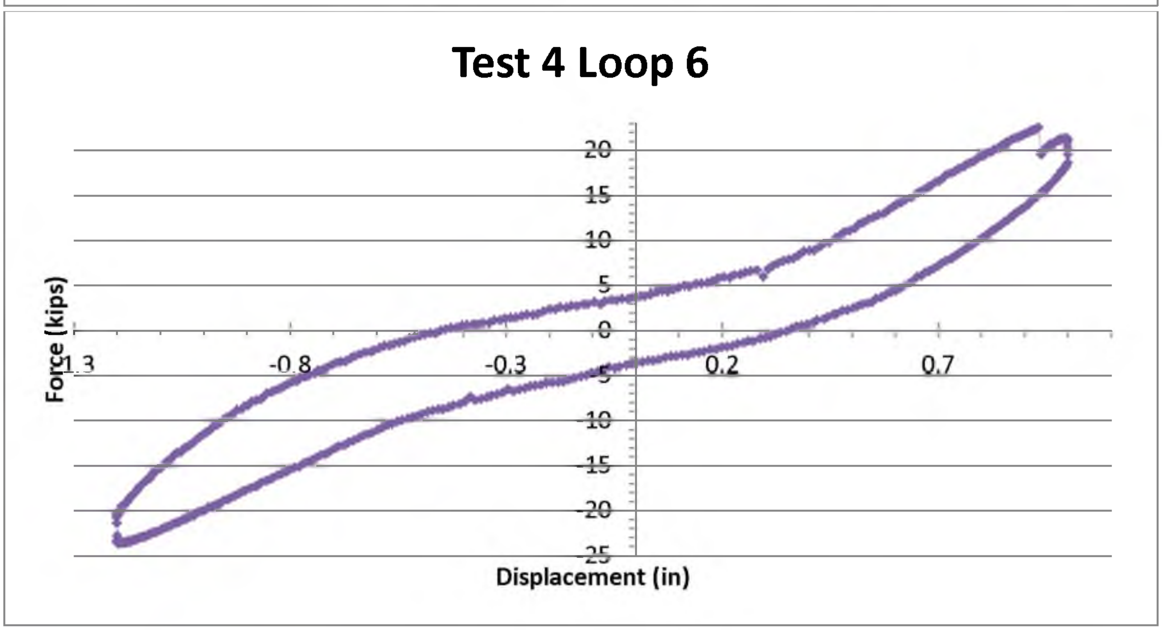




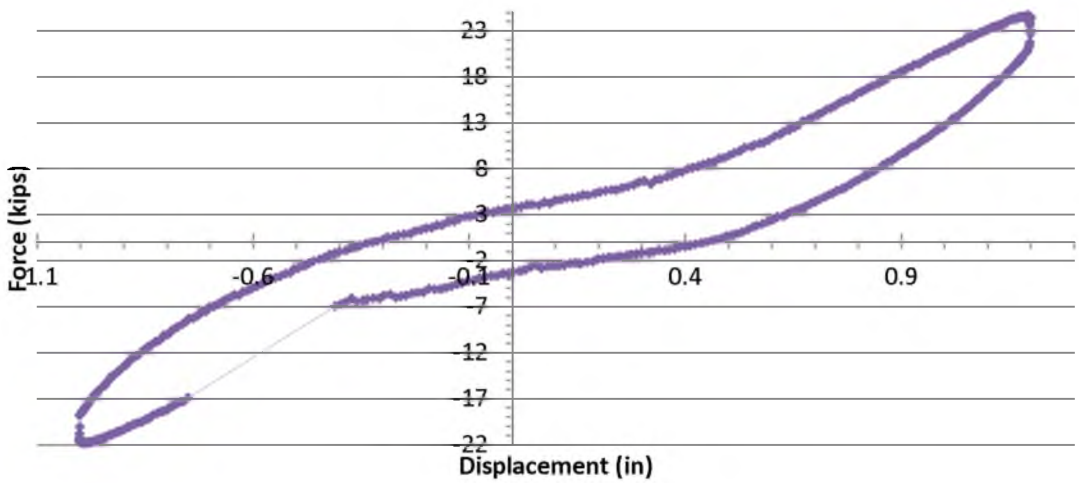

Test 4 Loop 3
13
8
3
-2
-7
-12
-17
-0.61
-0.41
-0.21
-0.01
0.19
0.39
Force (kips)
Displacement (in)


Test 4 Loop 4
15
10
5
0
-5
-10
-15
-20
-0.81
-0.61
-0.41
-0.21
-0.01
0.19
0.39
0.59
Force (kips)
Displacement (in)

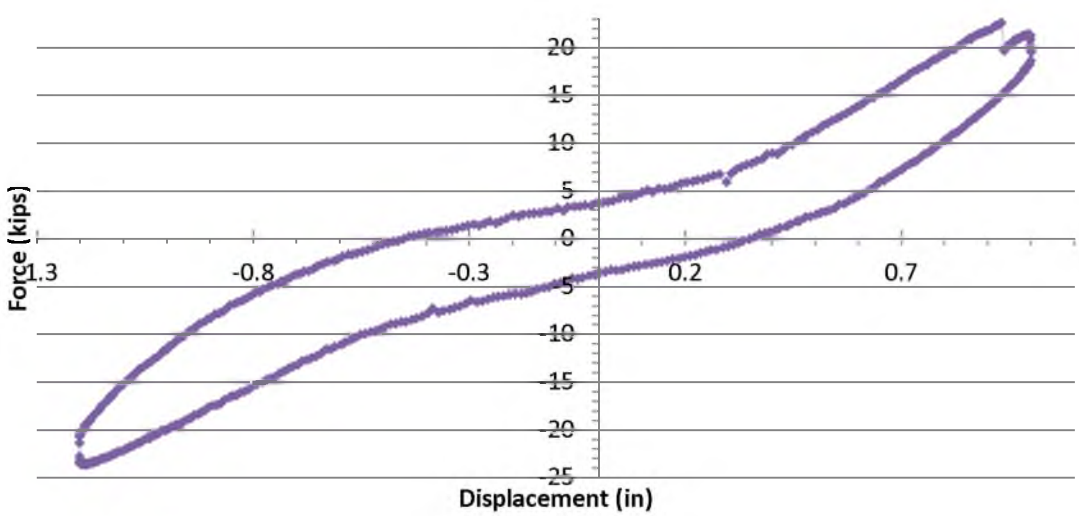

Test 4 Loop 5
Force (kips)
Displacement (in)
17
12
7
2
-3
-8
-13
-18
-23
-1.1
-0.9
-0.7
-0.5
-0.3
-0.1
0.1
0.3
0.5
0.7

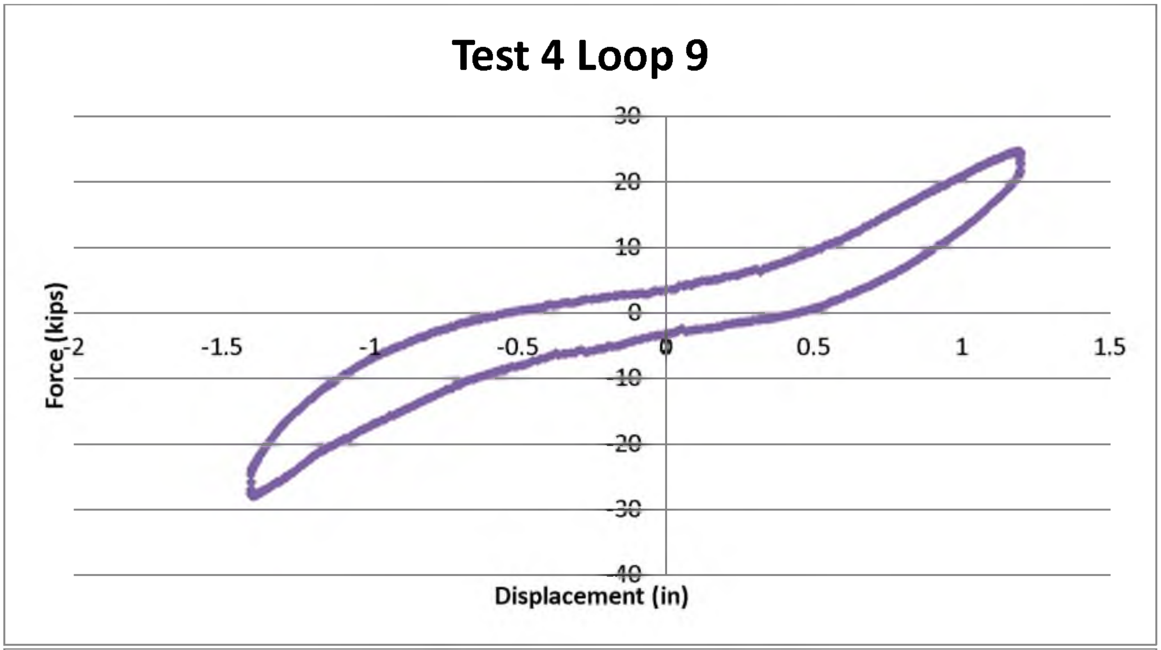

Test 4 Loop 6
Force (kips)
Displacement (in)
20
15
10
5
0
-5
-10
-15
-20
-25
-1.3
-0.8
-0.3
0.2
0.7

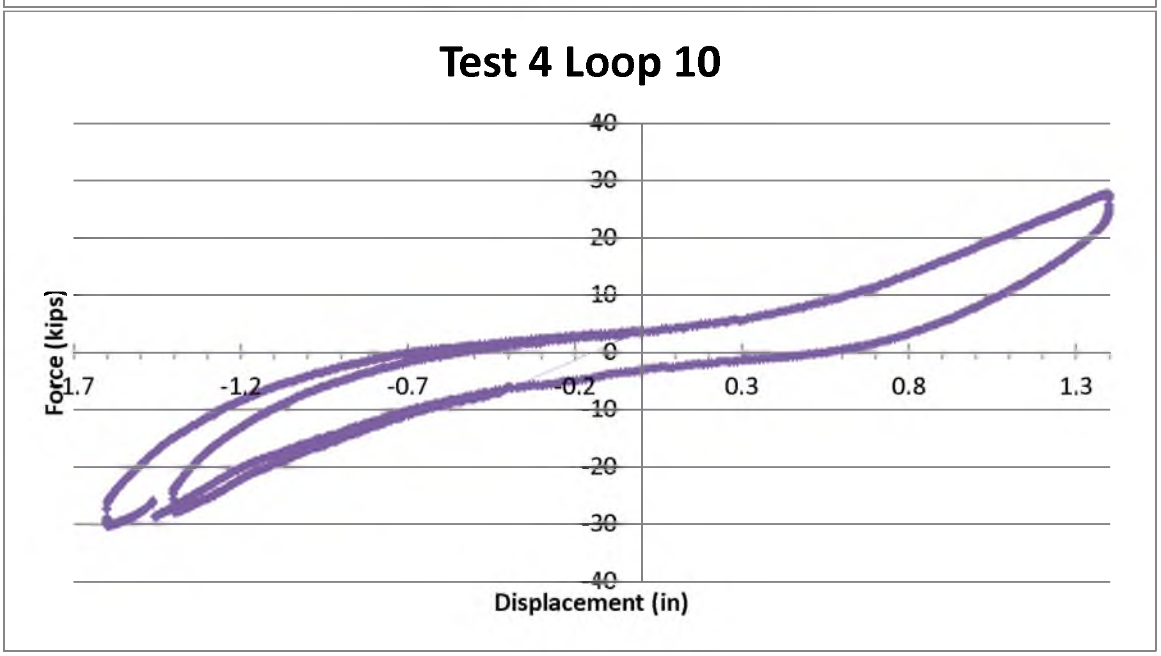
Test 4 Loop 7

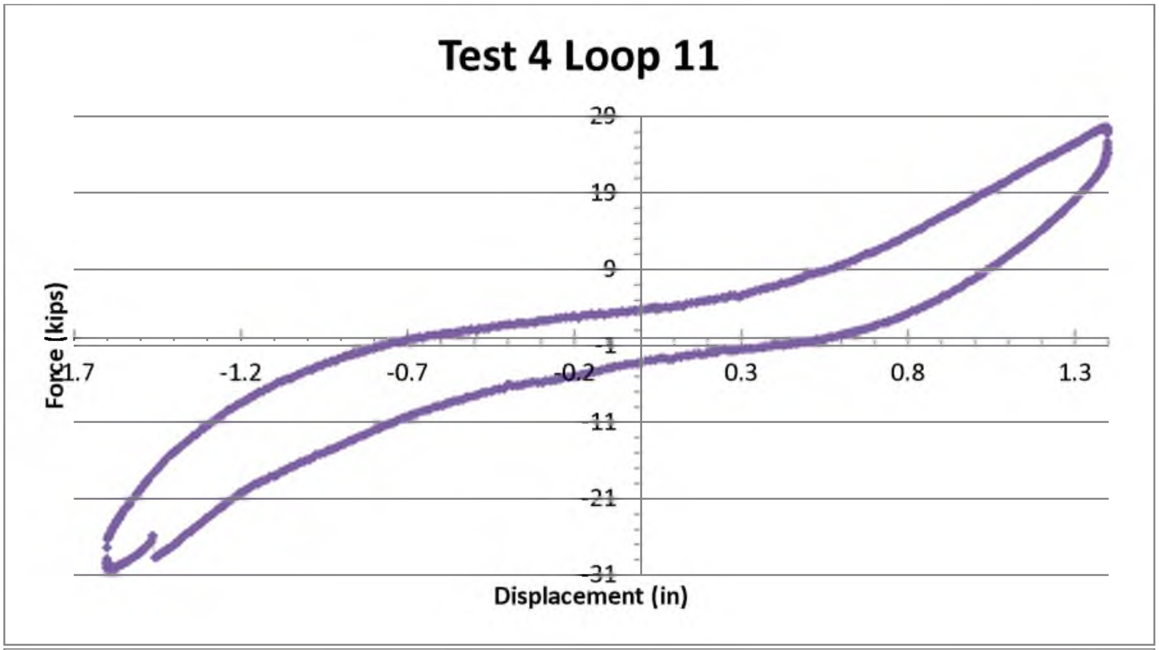


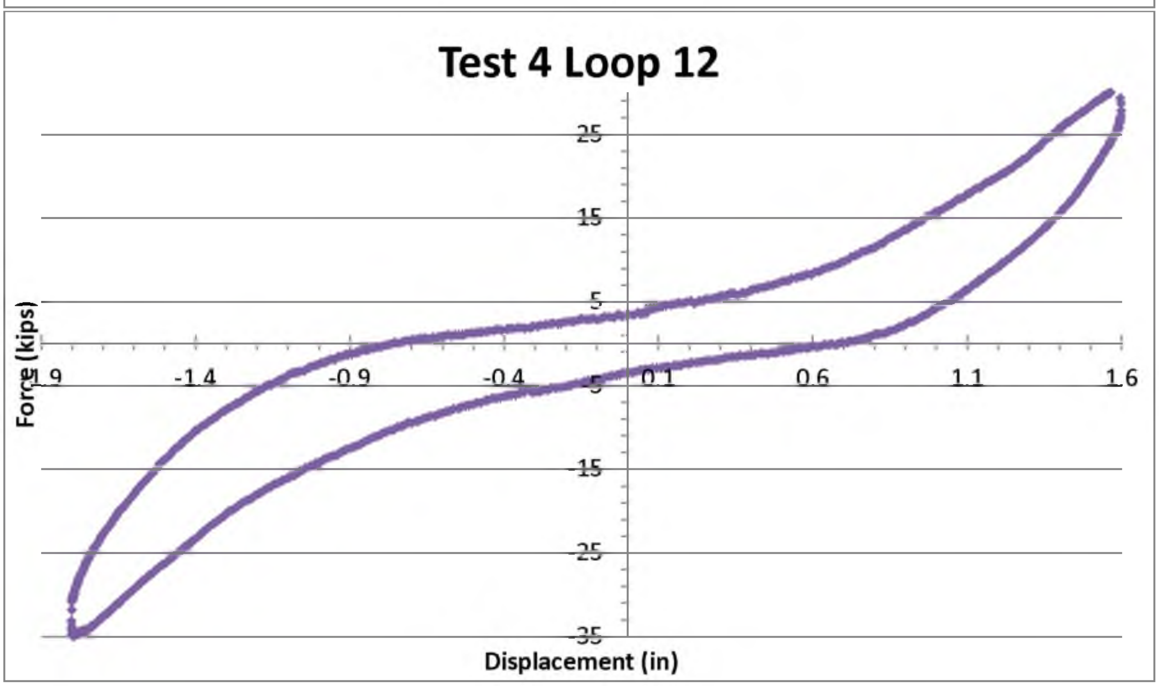
Test 4 Loop 8

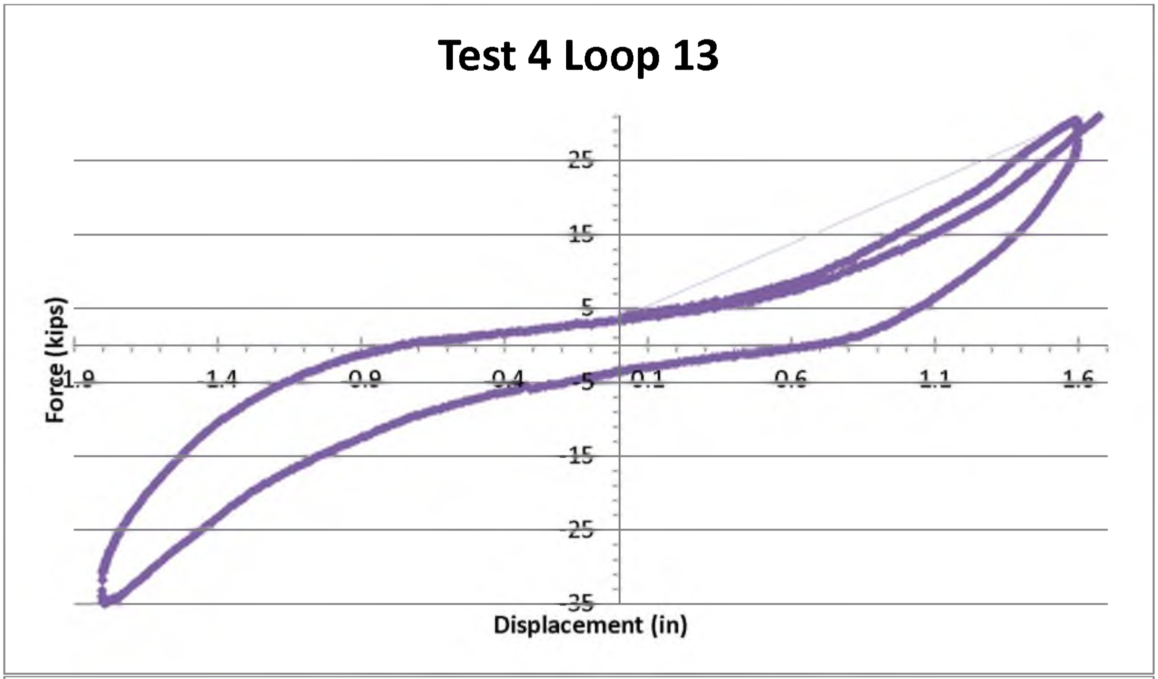



Test 4 Loop 9
30
20
10
0
-10
-20
-30
-40
-2
-1.5
-1
-0.5
0
0.5
1
1.5
Force (kips)
Displacement (in)

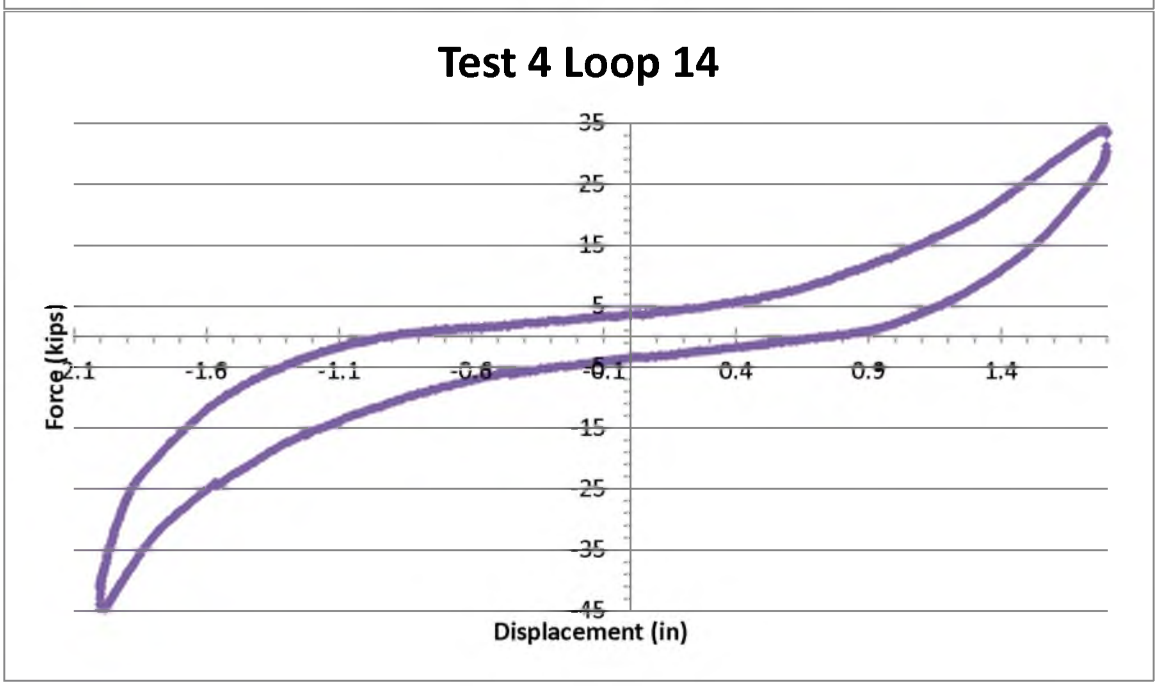

Test 4 Loop 10
40
30
20
10
0
-10
-20
-30
-40
-1.7
-1.2
-0.7
-0.2
0.3
0.8
1.3
Force (kips)
Displacement (in)


Test 4 Loop 11
29
19
9
-1
-11
-21
-31
-1.7
-1.2
-0.7
-0.2
0.3
0.8
1.3
Force (kips)
Displacement (in)

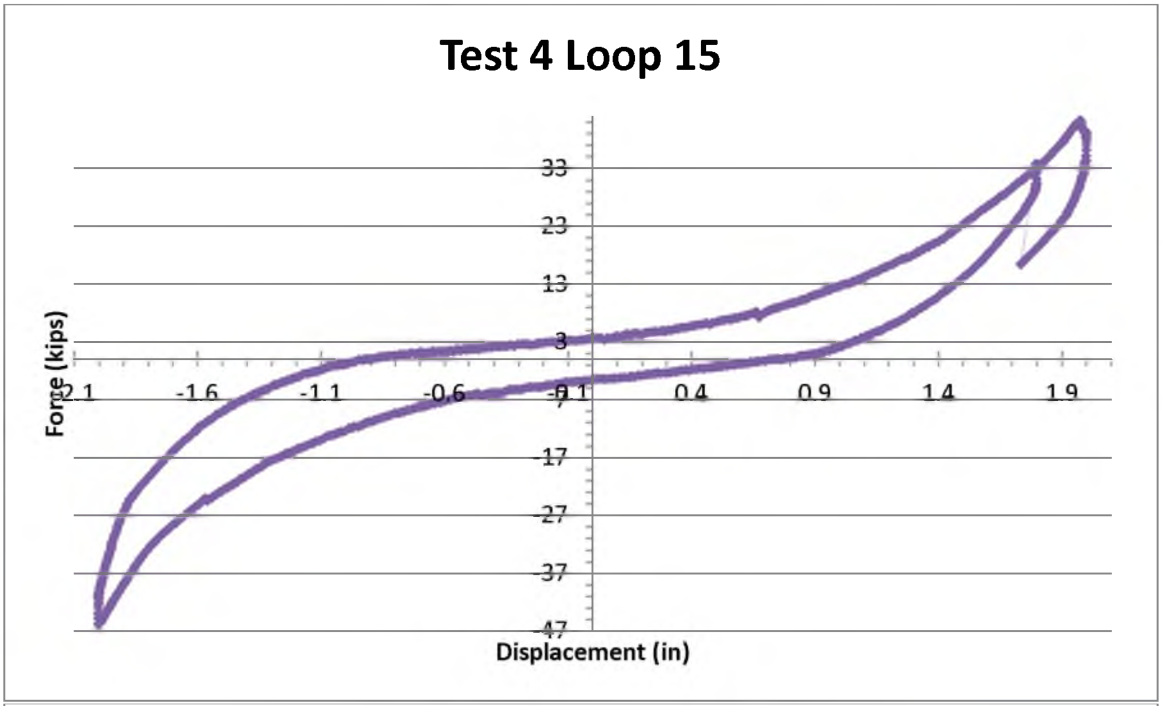

Test 4 Loop 12
25
15
5
-5
-15
-25
-35
-1.9
-1.4
-0.9
-0.4
0.1
0.6
1.1
1.6
Force (kips)
Displacement (in)

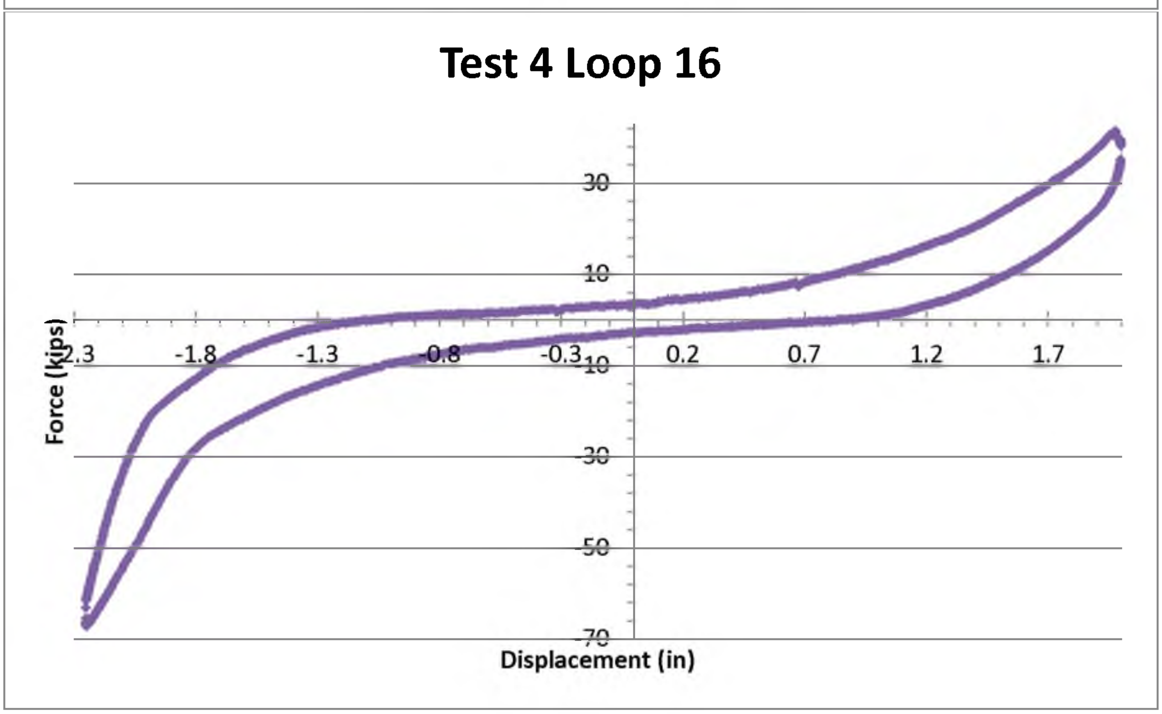


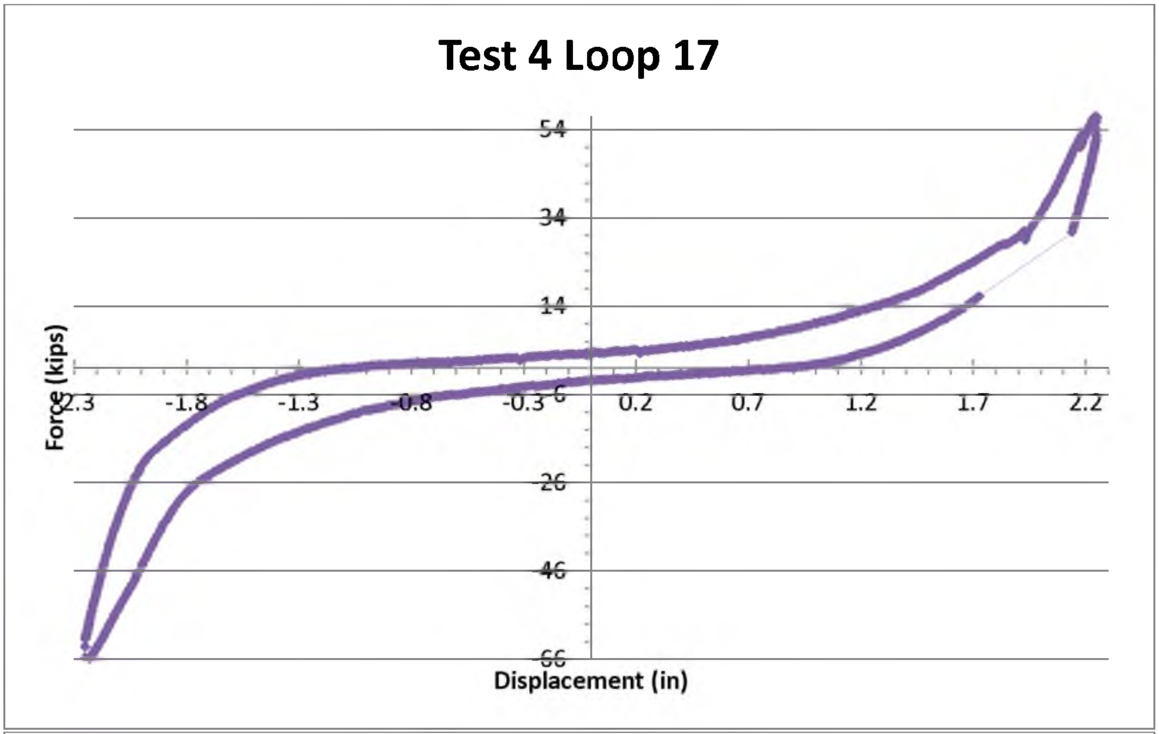
Test 4 Loop 13
25
15
5
-5
-15
-25
-35
-1.9
-1.4
-0.9
-0.4
0.1
0.6
1.1
1.6
Force (kips)
Displacement (in)

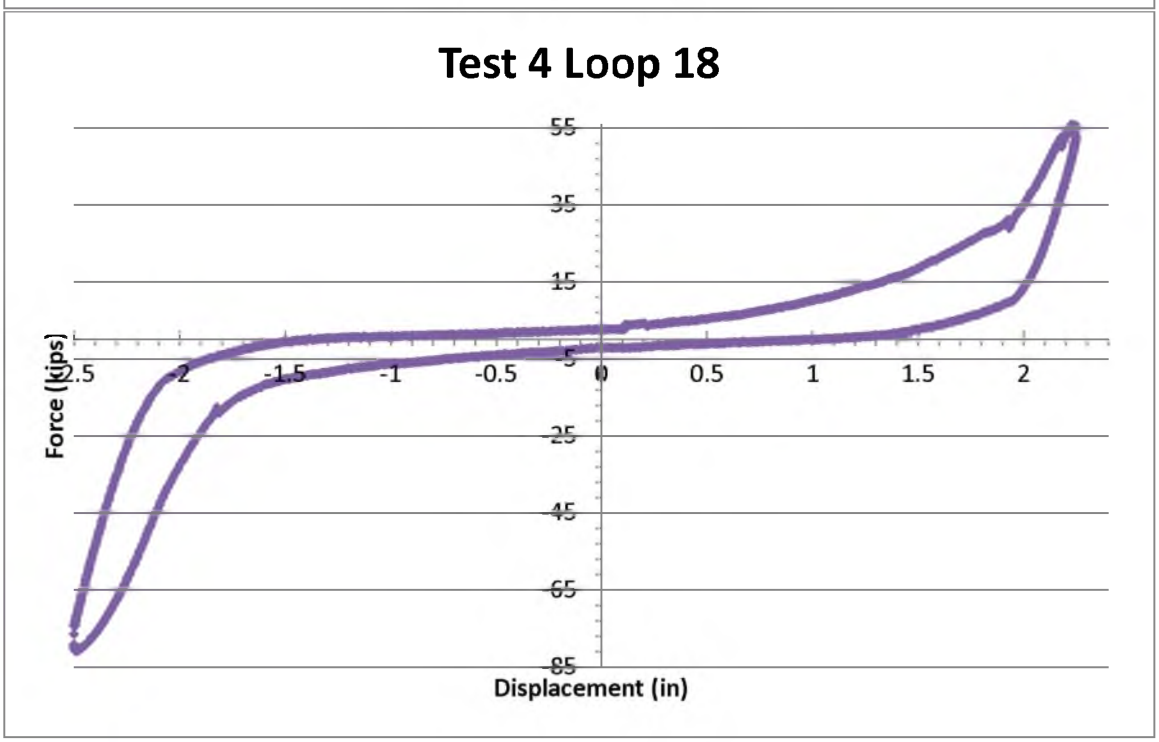


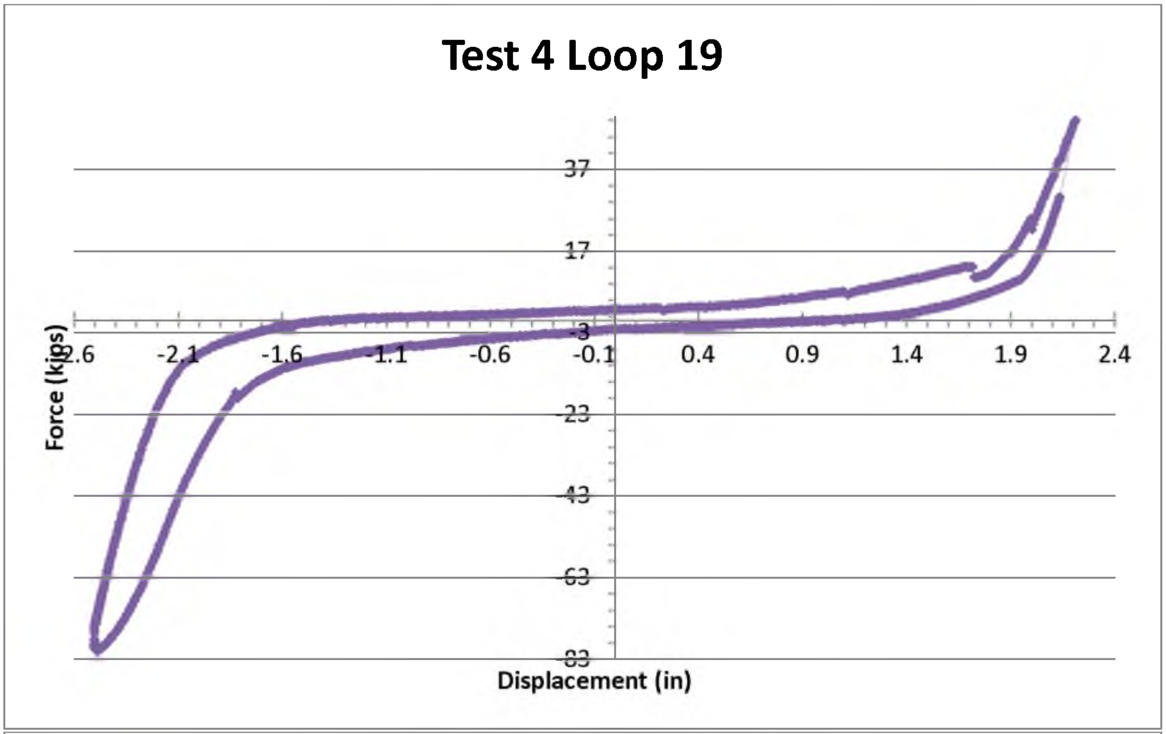
Test 4 Loop 14
35
25
15
5
-5
-15
-25
-35
-45
-2.1
-1.6
-1.1
-0.6
-0.1
0.4
0.9
1.4
Force (kips)
Displacement (in)

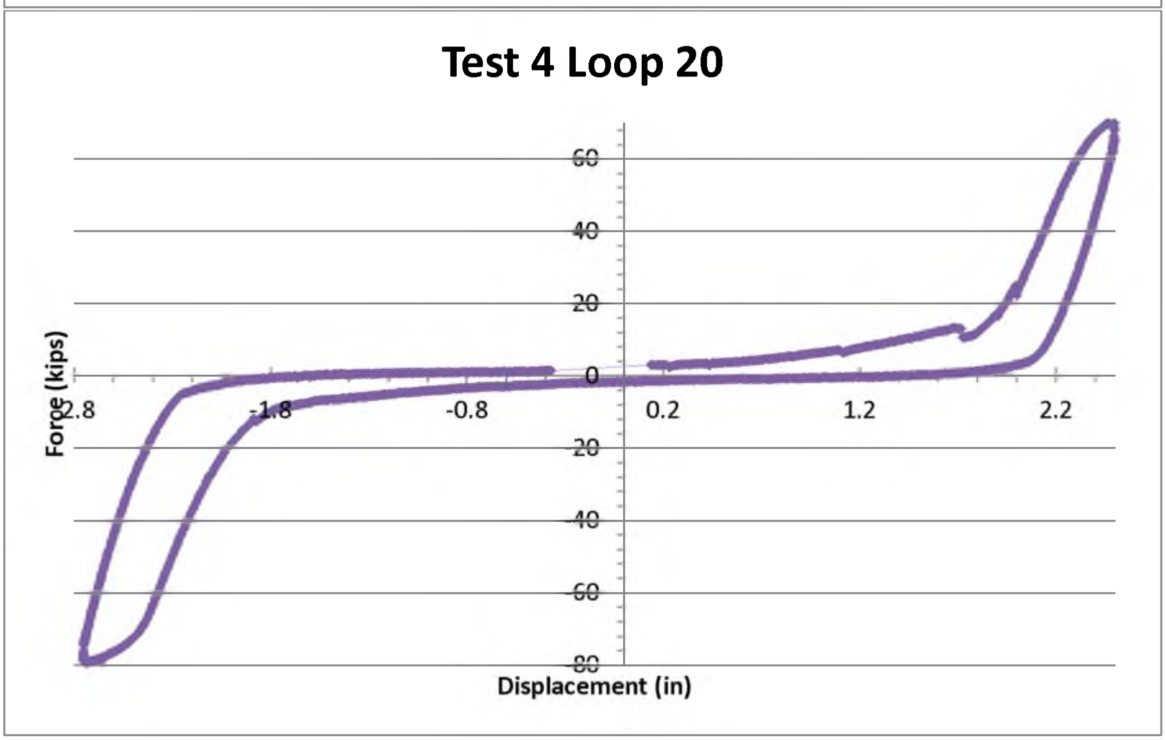

Test 4 Loop 15
33
23
13
3
-2.1
-1.6
-1.1
-0.6
-0.1
0.4
0.9
1.4
1.9
-7
-17
-27
-37
-47
Force (kips)
Displacement (in)

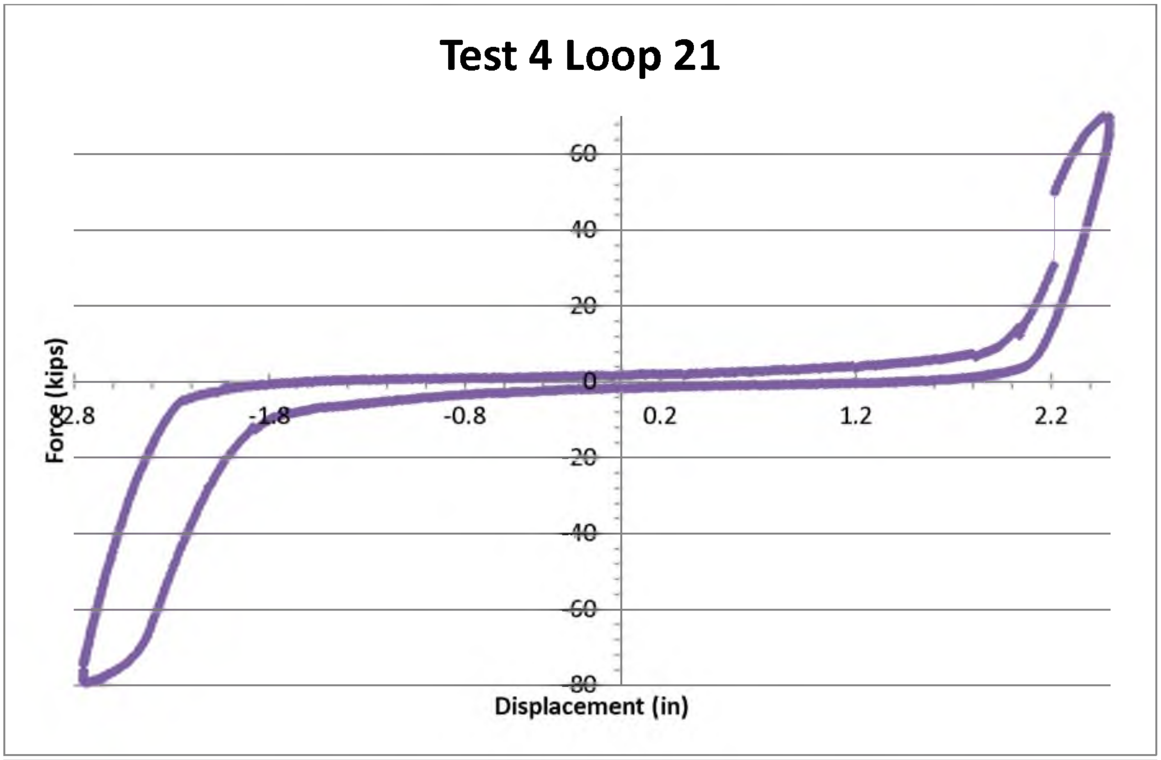

Test 4 Loop 16
30
10
-2.3
-1.8
-1.3
-0.8
-0.3
0.2
0.7
1.2
1.7
-10
-30
-50
-70
Force (kips)
Displacement (in)

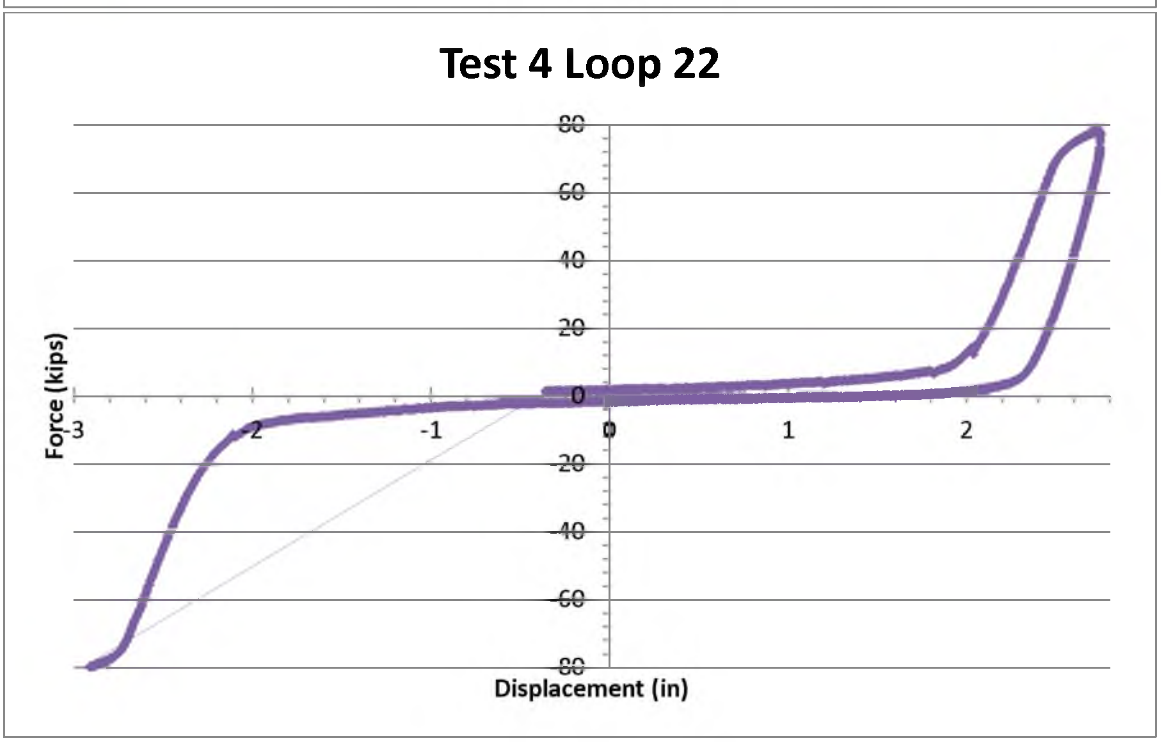

Test 4 Loop 17
Force (kips)
Displacement (in)
54
34
14
-6
-26
-46
-66
-2.3
-1.8
-1.3
-0.8
-0.3
0.2
0.7
1.2
1.7
2.2

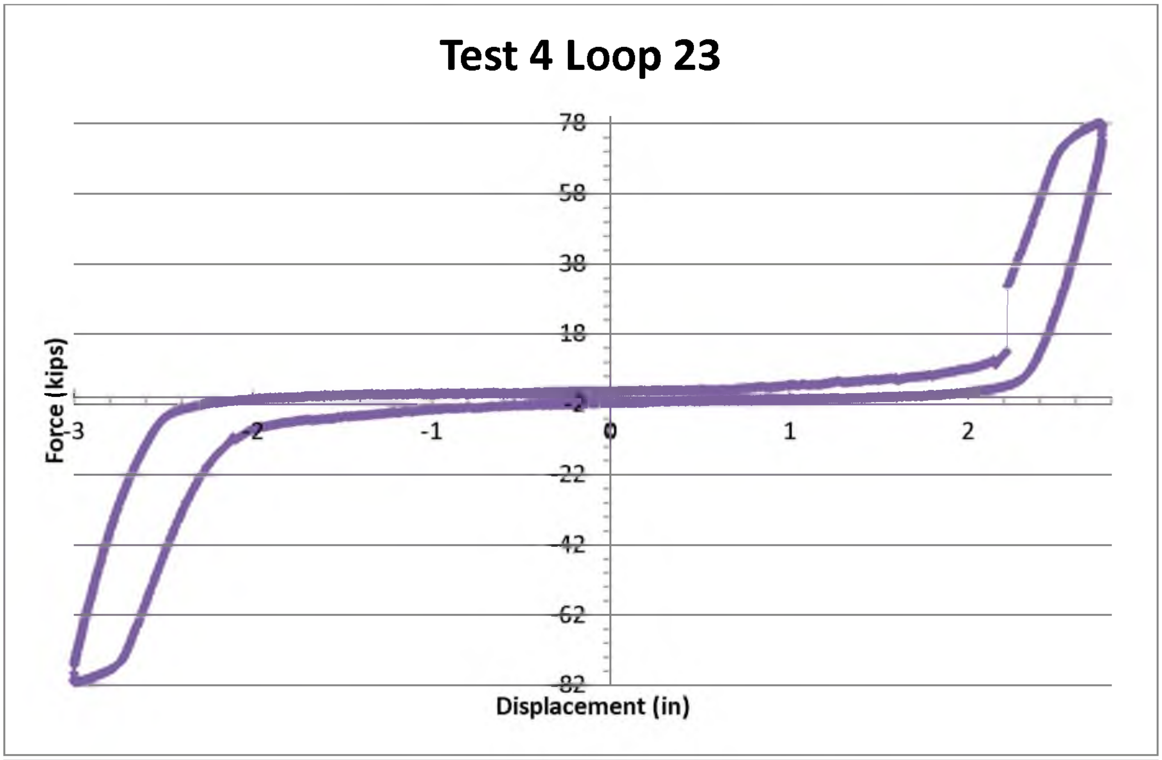

Test 4 Loop 18
Force (kips)
Displacement (in)
55
35
15
-5
-25
-45
-65
-85
-2.5
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2

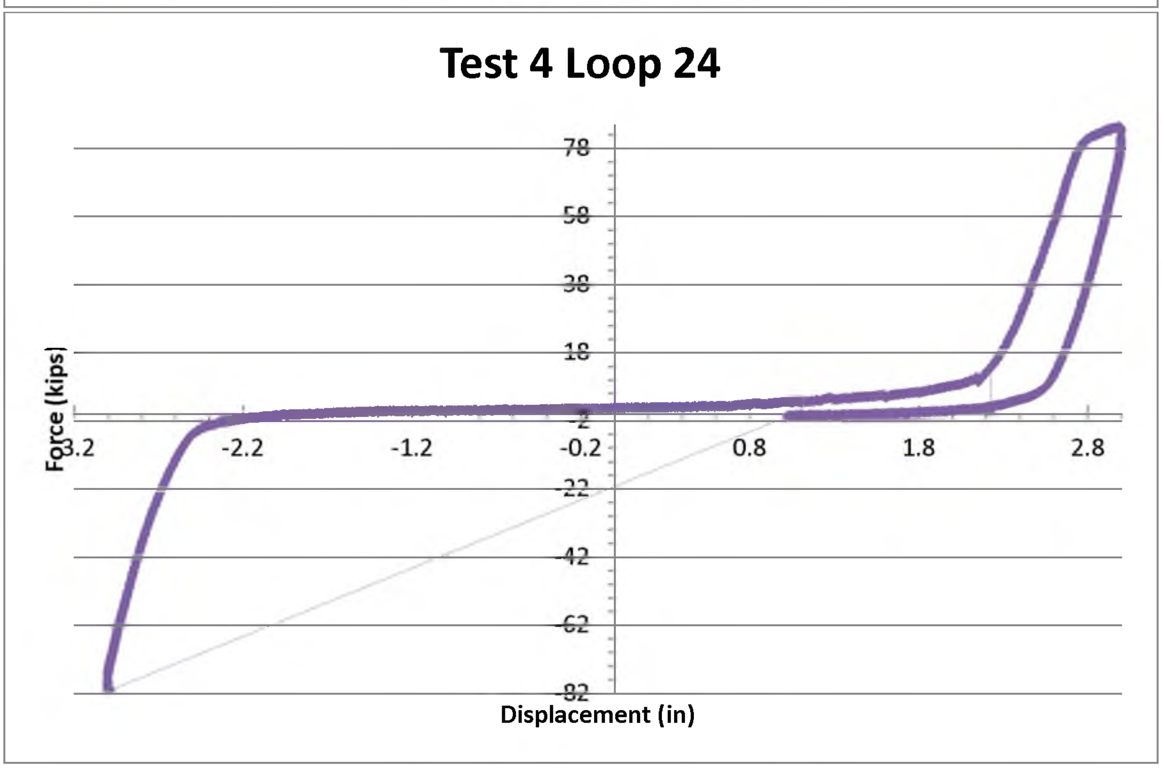

Test 4 Loop 19
37
17
-3
-2.6
-2.1
-1.6
-1.1
-0.6
-0.1
0.4
0.9
1.4
1.9
2.4
-23
-43
-63
-83
Force (kips)
Displacement (in)

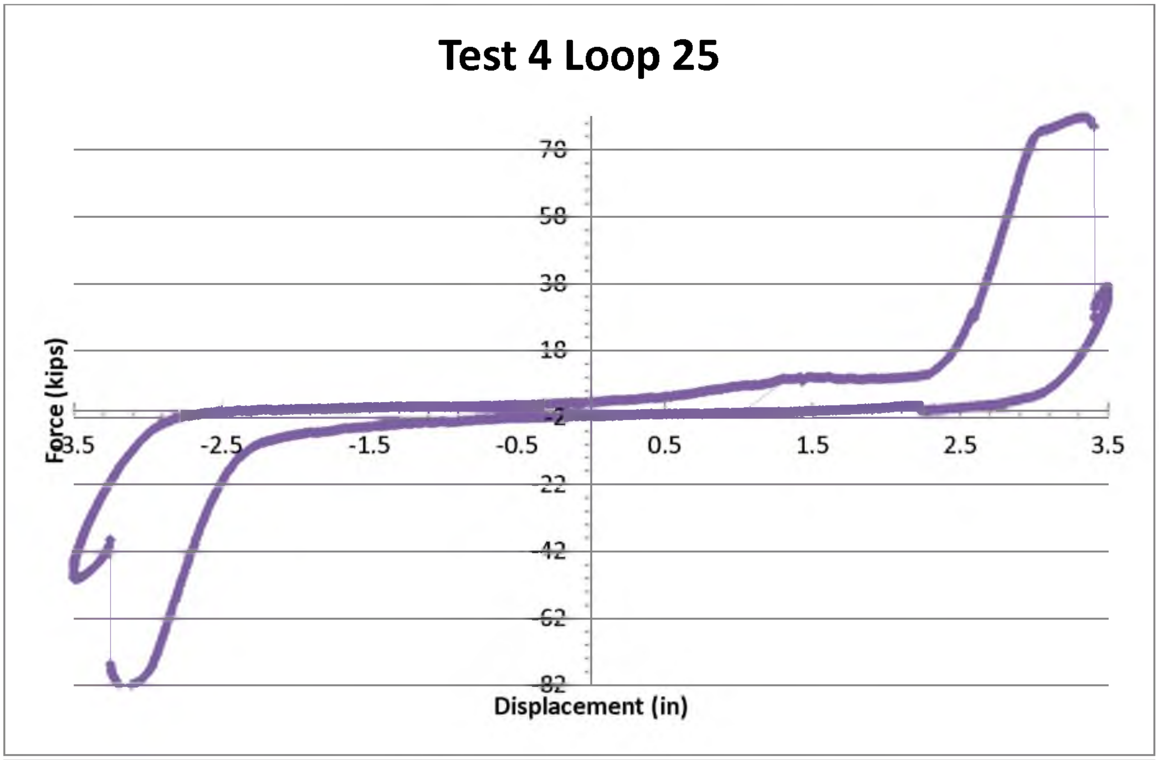

Test 4 Loop 20
60
40
20
0
-2.8
-1.8
-0.8
0.2
1.2
2.2
-20
-40
-60
-80
Force (kips)
Displacement (in)

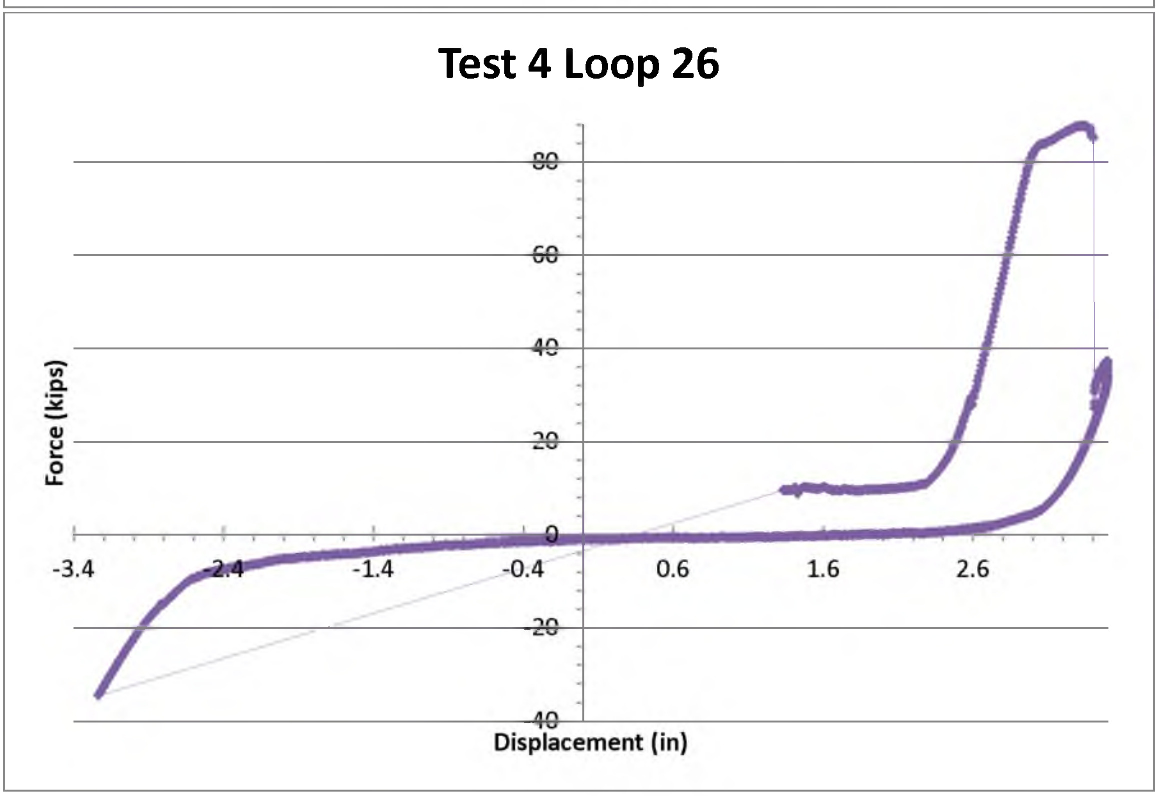

Test 4 Loop 21
60
40
20
0
-20
-40
-60
-80
-2.8
-1.8
-0.8
0.2
1.2
2.2
Force (kips)
Displacement (in)

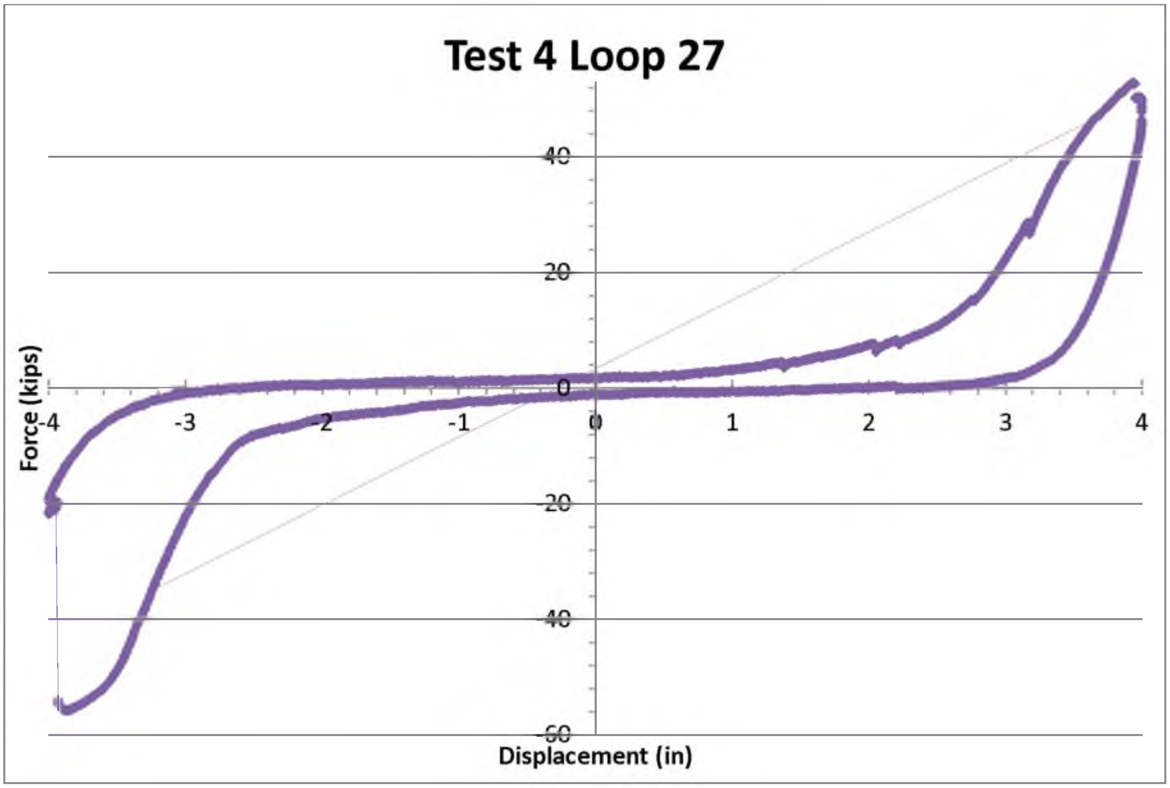

Test 4 Loop 22
80
60
40
20
0
-20
-40
-60
-80
-3
-2
-1
0
1
2
Force (kips)
Displacement (in)

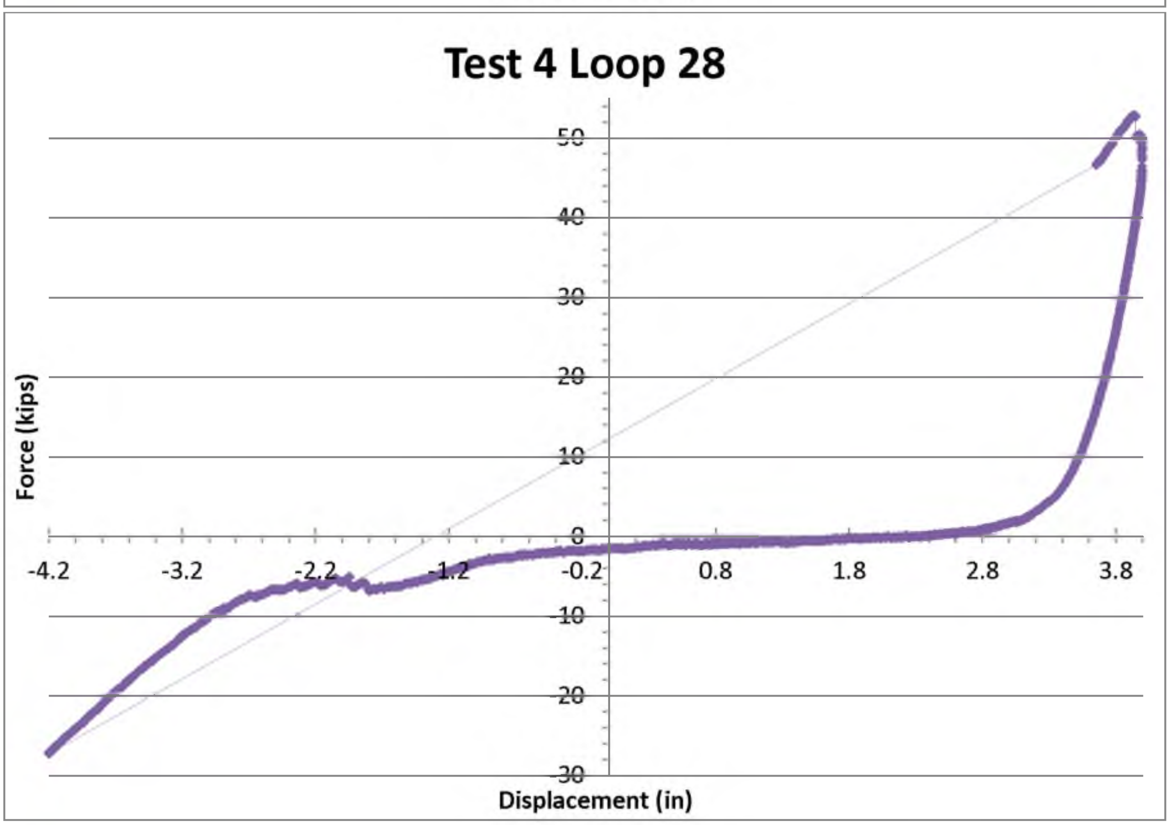

Test 4 Loop 23
78
58
38
18
-2
-22
-42
-62
-82
-3
-2
-1
0
1
2
Force (kips)
Displacement (in)

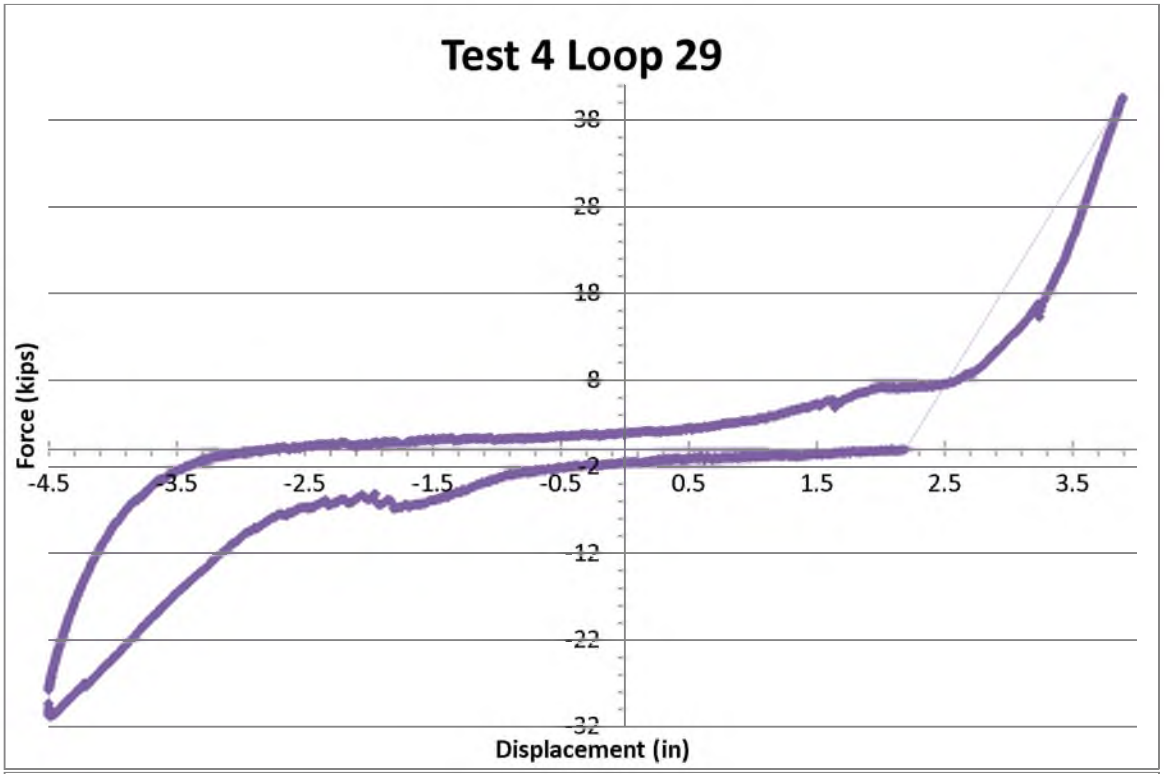

Test 4 Loop 24
78
58
38
18
-2
-22
-42
-62
-82
-3.2
-2.2
-1.2
-0.2
0.8
1.8
2.8
Force (kips)
Displacement (in)


Test 4 Loop 25
Force (kips)
Displacement (in)
78
58
38
18
-2
-22
-42
-62
-82
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
3.5

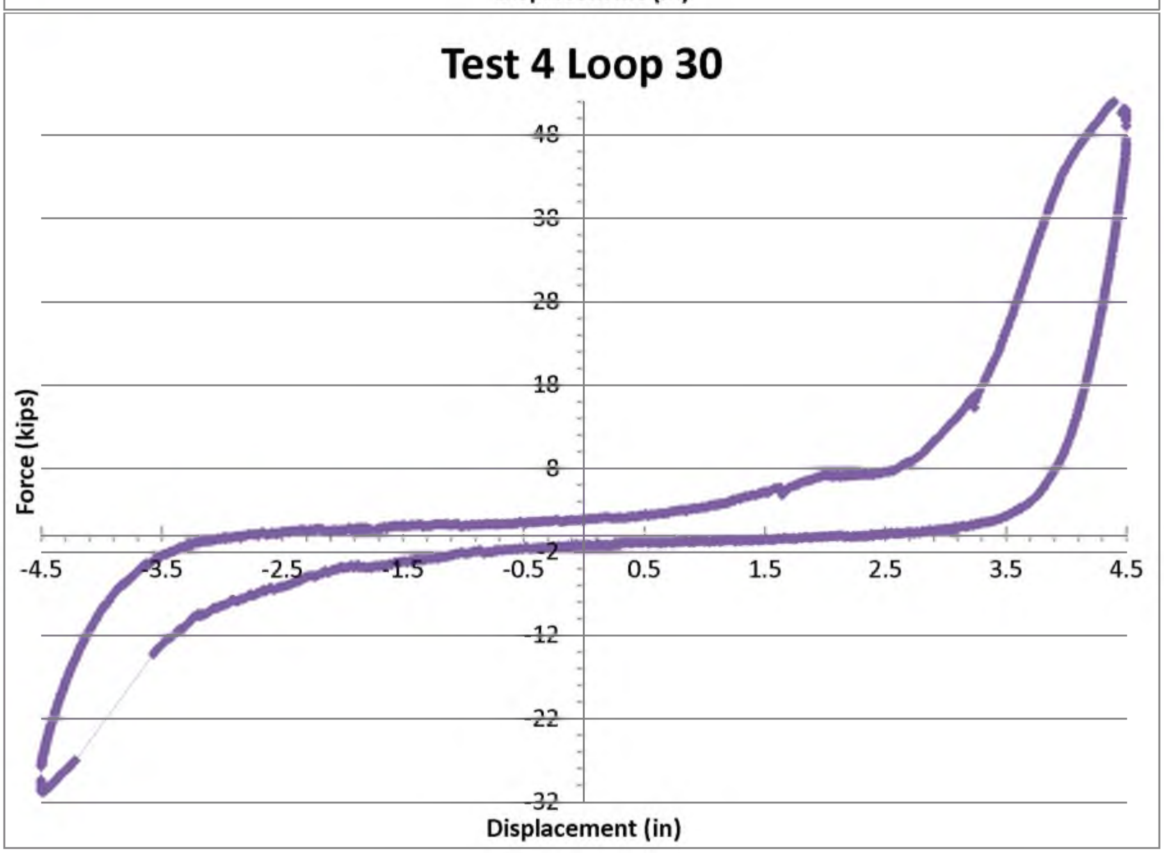

Test 4 Loop 26
Force (kips)
Displacement (in)
80
60
40
20
0
-20
-40
-3.4
-2.4
-1.4
-0.4
0.6
1.6
2.6


Test 4 Loop 27
Force (kips)
Displacement (in)
40
20
0
-20
-40
-60
-4
-3
-2
-1
0
1
2
3
4

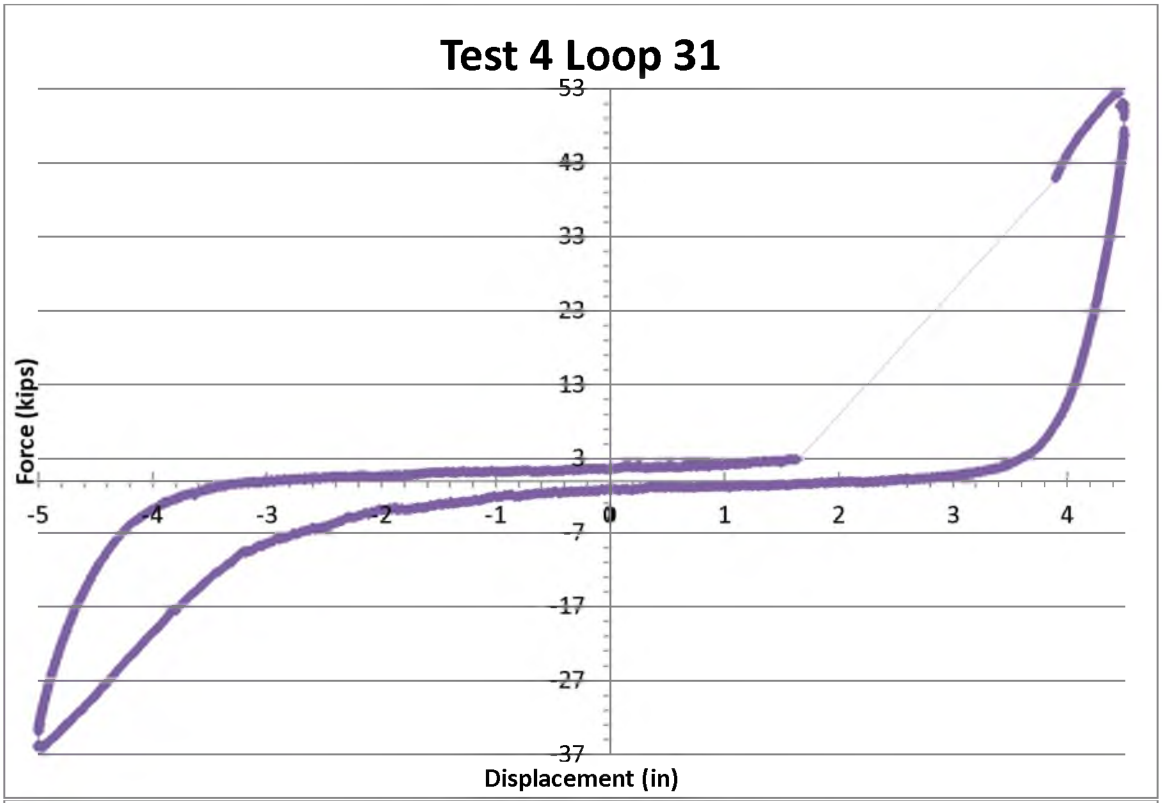

Test 4 Loop 28
Force (kips)
Displacement (in)
50
40
30
20
10
0
-10
-20
-30
-4.2
-3.2
-2.2
-1.2
-0.2
0.8
1.8
2.8
3.8



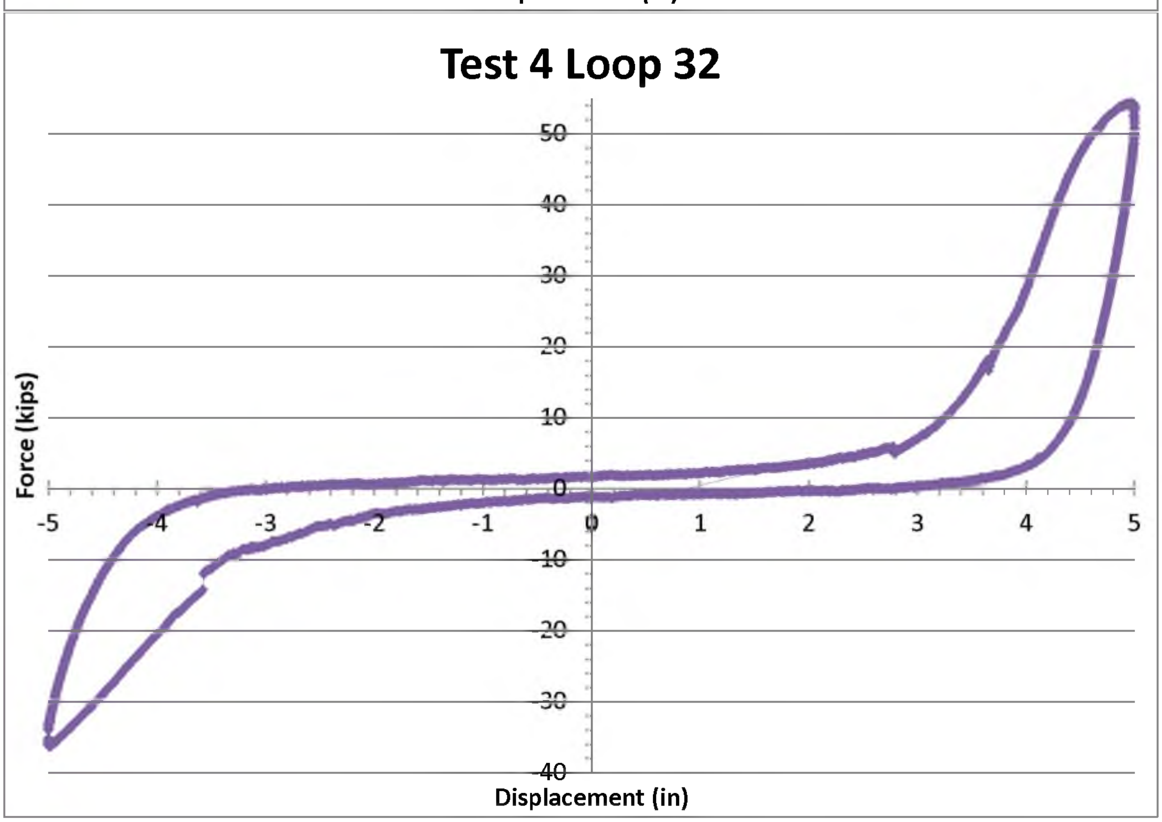
Test 4 Loop 29
Force (kips)
Displacement (in)
38
28
18
8
-2
-12
-22
-32
-4.5
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
3.5



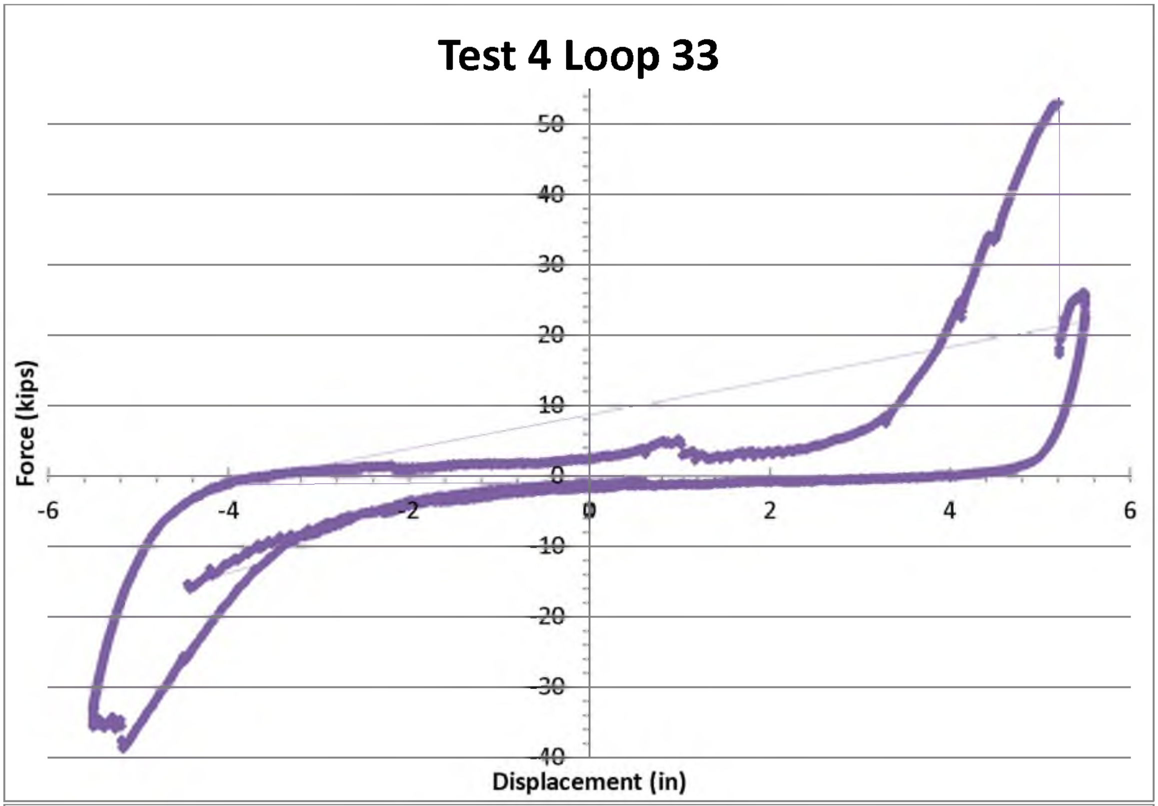
Test 4 Loop 30
Force (kips)
Displacement (in)
48
38
28
18
8
-2
-12
-22
-32
-4.5
-3.5
-2.5
-1.5
-0.5
0.5
1.5
2.5
3.5
4.5

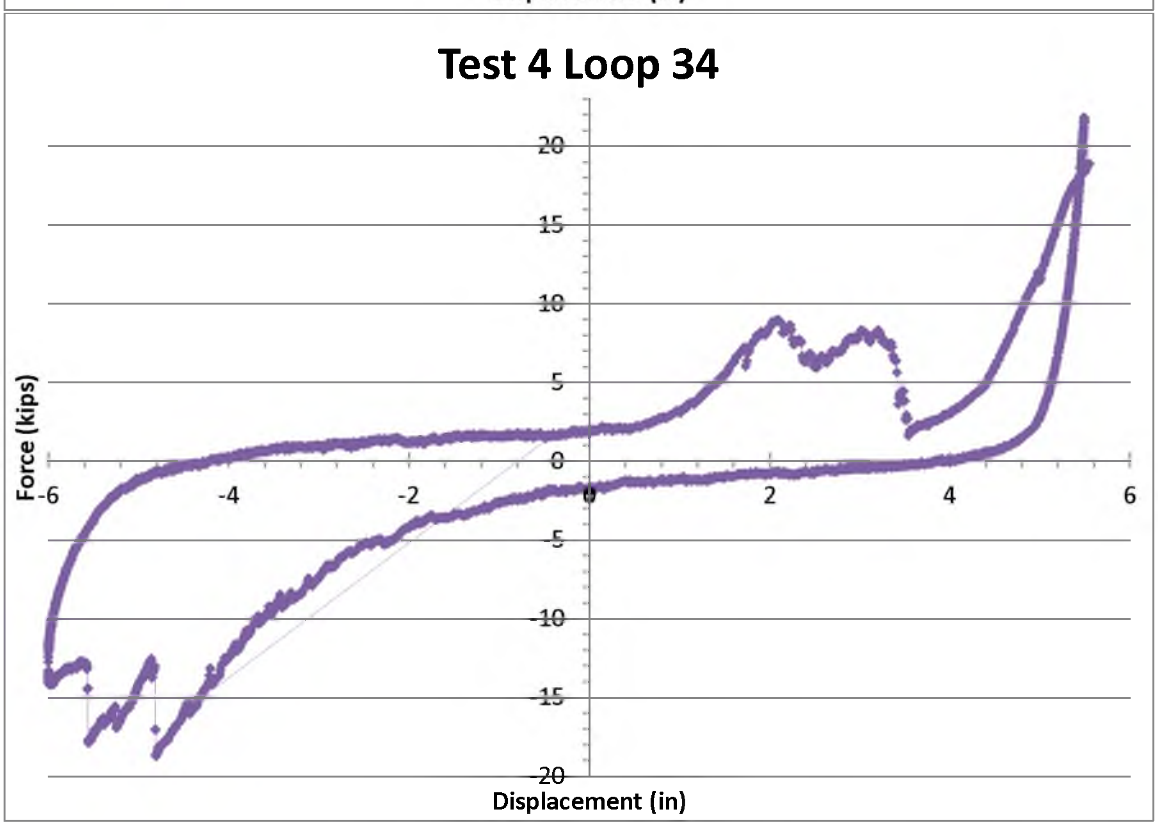


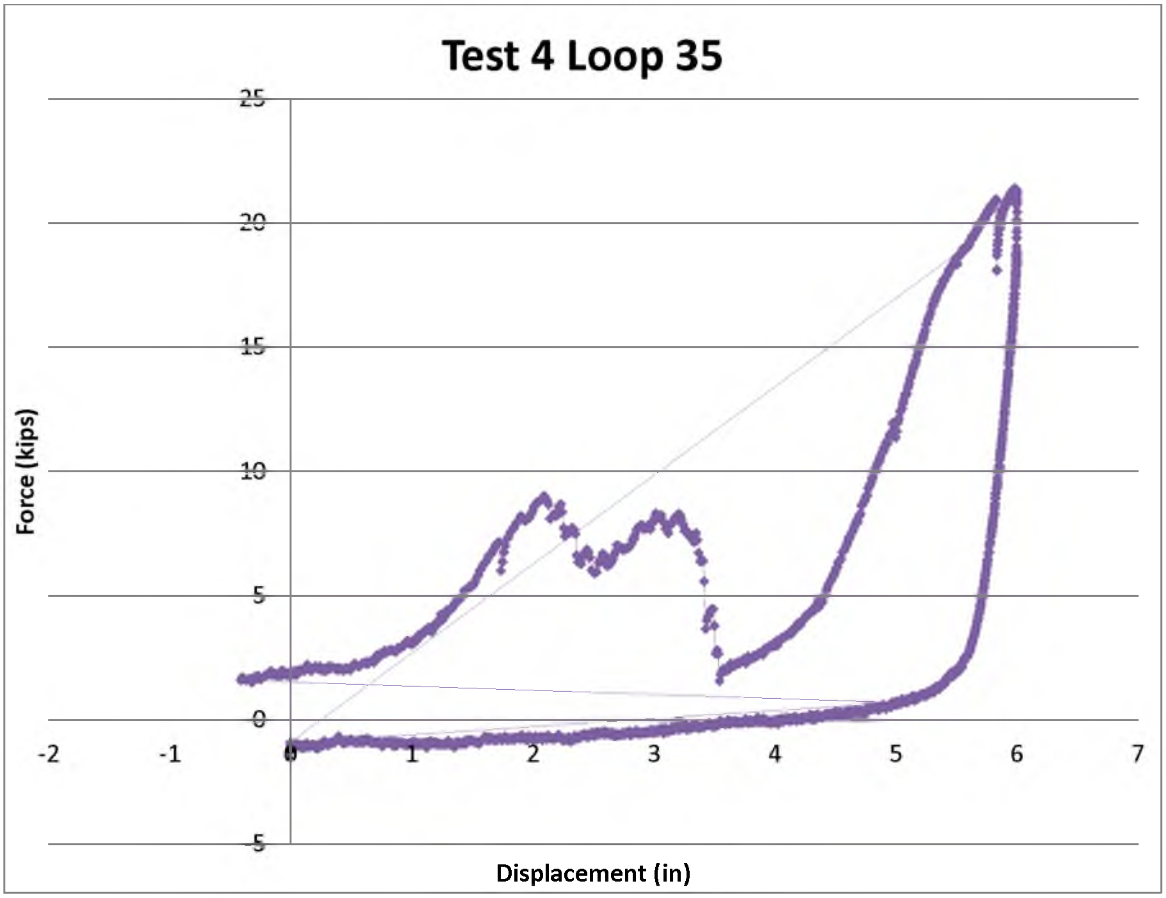
Test 4 Loop 31
Force (kips)
Displacement (in)
53
43
33
23
13
3
-7
-17
-27
-37
-5
-4
-3
-2
-1
0
1
2
3
4



Test 4 Loop 32
Force (kips)
Displacement (in)
50
40
30
20
10
0
-10
-20
-30
-40
-5
-4
-3
-2
-1
0
1
2
3
4
5


Test 4 Loop 33
Force (kips)
50
40
30
20
10
0
-10
-20
-30
-40
-6
-4
-2
0
2
4
6
Displacement (in)


Test 4 Loop 34
Force (kips)
20
15
10
5
0
-5
-10
-15
-20
-6
-4
-2
0
2
4
6
Displacement (in)


Test 4 Loop 35
Force (kips)
Displacement (in)
25
20
15
10
5
0
-5
-2
-1
0
1
2
3
4
5
6
7

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